FROST SUSCEPTIBILITY OF SOILS

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FROST SUSCEPTIBILITY OF SOILS

by

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Master's Thesis

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ABSTRACT

This report is the result of a research project undertaken by the author to review the frost susceptibility criteria for soils and to evaluate new approaches to the susceptibility problem. In order to evaluate the grain size criteria, the author, in conjunction with a literature review, performed freezing tests on five different gradations of the same material (Ottawa Sand). The specimens were subjected to open system freezing conditions at a constant surface temperature. Three series of tests were conducted, each at a different surface temperature. The results of these tests are presented.

The use of the "air-intrusion value" as suggested by Williams of the National Research Council of Canada, as a determination of frost susceptibility is also evaluated. In this evaluation, air-intrusion values of the test materials were determined. Calculations were made to determine the surcharge loading required to stop heave action. Freezing tests were performed to verify these calculations. The results of these tests are presented. Based upon these results, a modification to William's calculation procedure is proposed.

Finally, a review of the testing procedure is given and improvements are suggested to help those who might be interested in further investigation into the use of the air-intrusion value.

GLOSSARY

The following list of terms and symbols are presented to assist the reader in understanding this thesis. Where units are normally associated with a term or symbol, the appropriate units are listed in parentheses following the description. For brevity, the following symbols are used: Length, L; Mass, M; Time, T; Temperature, θ, Force, F.

Example: FL^{-2} refers to units of force per unit area.

DEFINITIONS

Definitions of the following terms used in this thesis were taken principally from a list prepared and approved by the Highway Research Board (HRB) Committee on Frost Heave and Frost Action in Soils.[11] Definitions not taken from the above mentioned list are so noted and reference is made as to its source.

Term	Definition
Air-Intrusion[35]	The critical pressure difference at which air-filled channels can spread through a soil sample instead of being confined to a thin surface layer (FL^{-2}).
Closed System	A condition in which no source of free water is available during the freezing process beyond that contained originally in the voids of the soil.
Freezing Point	Temperature at which ice and water are in equilibrium.
Frost Action	A general term for the freezing and thawing of moisture in materials and on structures of which they are part or with which they are in contact.

GLOSSARY (continued)

Term	Definition
Frost Heave	The raising of a surface due to the formation of ice in the underlying soil.
Frost Line	The boundary between frozen and unfrozen soil.
Frost Penetration Rate	The average rate of penetration of the $0^{o}C$ isotherm, in inches per day, determined from a plot of temperature at depth below the surface versus time (LT^{-1}).
Frost Susceptible Soil	Soil in which significant (detrimental) ice segregation occurs when the requisite moisture and freezing conditions are present.
Ice Segregation	The growth of ice as distinct lenses, layers, veins and masses in soils, commonly oriented normal to the directions of heat loss.
Ice Lenses	Ice formation in soil occurring essentially parallel to each other, generally normal to the direction of heat loss, and commonly in repeated layers.
Non-Frost Susceptible Materials	Cohesionless materials such as: crushed rock, gravel, sand, slag and cinders in which significant (detrimental) ice segregation does not occur under normal freezing conditions.
Open System	A condition in which free water in excess of that contained originally in the voids of the soil is available to be moved to the surface of freezing, to form segregated ice in frost-susceptible soil.
Percentage of Heave	The ratio, expressed as a percentage, of the amount of heave to the depth of the frozen soil before freezing.

GLOSSARY (continued)

Term	Definition
Rate of Heave*	The average rate of heave, in millimeters per day, determined from a representative portion of a plot of heave versus time, in which the slope is relatively constant (LT^{-1}).
Surface Tension[31]	The concept that the surfaces of liquids are in a state of tension. The interaction of surface molecules causes a condition analogous to a surface subjected to tension. It is well-known that no skin of thin foreign surface really is in existence.

*Author's definition.

SYMBOLS

Symbol	Meaning
A	Area (L^2)
E_c	Chemical Potential (FL)
$E_c(p)$	Chemical Potential of Stated Pressure (FL)
K_o	Coefficient of Lateral Earth Pressure at Rest
P_a	Air Pressure (FL^{-2})
P_h	Internal Pressure of Bulk Solid (FL^{-2})
P_i	Internal Pressure of Ice (FL^{-2})
P_s	Internal Pressure of Crystal (FL^{-2})
P_w	Pressure of Water (FL^{-2})
r_c	Radius of Capillary (L)
T_s	Interfacial Free Energy (Surface Tension)(FL^{-1})
T_{aw}	Surface Tension, Air-Water (FL^{-1})
T_{iw}	Surface Tension, Ice-Water (FL^{-1})
V	Volume (L^3)
v^s	Molar Volume of Solid, Molecular Weight/Specific Gravity (L^3)
$\sigma_{1,2,3}$	Principal Total Stresses (FL^{-2})
σ_{oct}	Octahedral Normal Total Stress (FL^{-2})

CHAPTER I

INTRODUCTION

Civil Engineering facilities (including roads, airfields and dams), are normally founded on or bounded with the Earth, near its outer surface. When these facilities are located in regions where seasonally frozen or perennially frozen ground (Permafrost) is encountered, problems associated with the freezing and thawing process become a major concern. Frost action in soils has been of concern to civil engineers and highway and airfield designers for many years. With the introduction of the automobile into our way of life and the development of heavy aircraft, the technical problems of frozen and thawed ground attained a real significance both from a practical as well as an economical point of view.

Generally, the conditions which influence frost action of soils can be divided into internal and external factors. External factors, such as climate and load, are outside the soil but influence it. Internal factors are those which belong to or are properties of the soil mass. Moisture content, soil structure, density, permeability, physical and chemical composition and thermal properties are but a few internal factors. The influence of these factors on a given soil mass is very complicated. It has been common practice to rate soils as frost susceptible or non-frost-susceptible based upon gradation criteria or heave action tests.

Numerous investigators have shown interest in frost action as is evident from the voluminous literature pertaining directly or indirectly to the subject. An excellent survey and review of this literature from 1765 to 1951 was prepared by Johnson[14*] in 1952. Frost susceptibility criteria up to 1961 were reviewed by Townsend and Csathy.[32] Cominsky, Cumberledge and Bhajandas[5]

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*Numbers correspond to references in Bibliography.

prepared a literature review in 1972. Anderson and Morgenstern[2] in their review of the mechanics of frozen ground for the Second International Conference on Permafrost (1973) observed that with regard to frost susceptibility testing there still exists a need for a more rapid test procedure. They noted that indirect tests suggested by the air-intrusion studies of Williams[35] showed promise in this regard.

The demand for high quality, stable foundations associated with increased construction efforts in Arctic and Subarctic areas is placing new emphasis on frost action technology. In many regions, the availability of readily available, good quality material is rapidly being depleted. It is imperative that the performance of soils with respect to frost action be properly evaluated. This requires that potentially frost susceptible soils be recognized and that the condition be treated as a unique engineering problem demanding a full analysis.

The purpose of this thesis is to review the frost susceptibility criteria of soils and to evaluate new approaches to the susceptibility problem.

CHAPTER II

LITERATURE REVIEW

General Discussion

Frost heaving of soils has been of interest to civil engineers for many years. The phenomenon of the raising of the ground surface associated with the freezing of soils seems to have been well-known by the 1700's. A full explanation of frost heaving was given by Runeberg in 1765 (see Beskow,[3] p. 1). Runeberg explained frost heaving as the result of expansion caused by the existing soil water (moisture) changing to ice. Johansson (see Beskow,[3] p. 3) is the first known investigator to find that during the freezing of fine-grained soil, water flows to the freezing layer increasing the water content. In his published experimental work of 1914, he used this observation to explain how heaving of soils occurred. Taber[29] in 1918, published the results of his early experiments in which he observed that the pressure effects accompanying freezing were due to the growth of ice crystals. This observation stimulated some interest in the phenomenon and Wyckoff[38] in discussing Taber's article verified the findings by his personal field observations of segregated ice found under piers which had raised from 1/2 to 2-3/4 inches during construction. Figure 1 shows his observation:

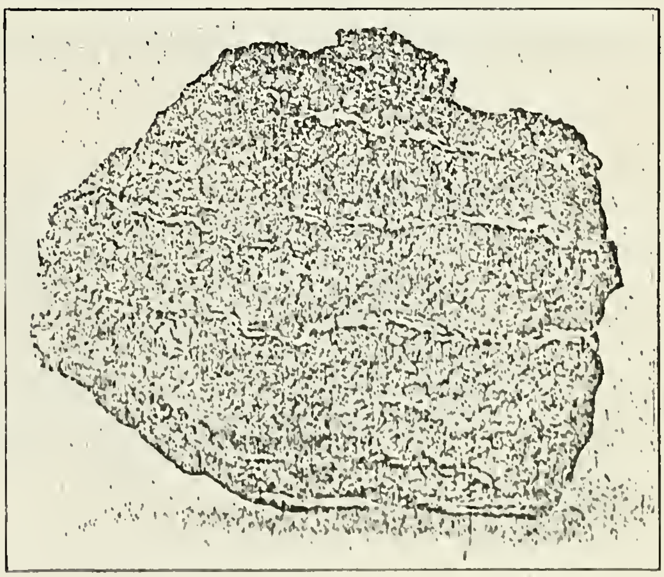

FIGURE 1. Six-inch Lump of Clay Laminated With Ice Formed When It Was In The Ground (after Wyckoff[38])

The American interest and investigations in the field began in the mid-1920's with the work of Taber and Casagrande. Taber[28,30] showed experimentally that the expansion of water due to freezing was not the fundamental cause of heaving as Runeberg had concluded. To verify this point, Taber replaced the water in the soil with other liquids which decrease in volume upon freezing. He then subjected these soils to freezing and observed that the soils still showed heaving during the freezing process. This resulting surface heaving could only be explained by the fact that the freezing liquid was transported within the soil to the freezing front and segregation of the soil and frozen liquid occurred. Taber[27] expressed his findings as follows:

> Frost heaving is due to the growth of ice crystals and not to change in volume. Pressure is developed in the direction of crystal growth which is usually determined chiefly by the direction of cooling. Excessive heaving results when water is pulled up through the soil to build up layers or lenticular masses of segregated ice, which grow in thickness because water molecules are pulled into the thin film that separates the growing columnar ice crystals from the underlying soil particles.

The existence of this thin film has been demonstrated convincingly by Corte,[6,7] Uhlman et al.[34] and Freden.[10]

Casagrande,[4] as a result of field observations in New Hampshire and tests conducted at the Massachusetts Institute of Technology during the winter of 1928-29, concluded the following:

> Under natural freezing conditions and with sufficient water supply, one should expect considerable ice segregation in non-uniform soils containing more than three percent of grains smaller than 0.02 mm., and in very uniform soils containing more than ten percent smaller than 0.02 mm. No ice segregation was observed in soils containing less than one percent of grains smaller than 0.02 mm., even if the ground water level was as high as the frost line.

The aforementioned observations have become known as the Casagrande Criteria, or Rule-of-Thumb criteria. These were not meant to be absolute indicators but only engineering guidelines. Over the course of time, however, they have been adopted into many specifications and have become the accepted criteria both in the United States and other countries. Some agencies have recognized the limitations and therefore have modified their criteria to coincide with local field observations. Casagrande himself was the first to point out that his observations were for soils from New Hampshire and that judgment must be used in extending this to other areas.

Parallel with the work of Taber in the United States, the Swedish scientist, Dr. Gunnar Beskow was performing extensive investigations into the mechanics of frost action in soils. The results of his works were published in 1935 and translated into English in 1947.[3] One of his investigations considered the relationship of grain size to frost action. On the basis of these observations, Figure 2 was constructed. This shows a relationship between frost-susceptible and non-frost-susceptible moraine soils or similar mixtures. For normal sediments, Beskow found the limiting grain size as the point where 30% of material is finer than 0.062 mm or 55% is finer than 0.125 mm. Soils coarser than this are definitely non-frost heaving. It is important to note that Beskow defines "essentially non-frost-heaving" as that which is less than 3 to 4 cm of heave during a winter.

Particle Size Consideration

The most widely used physical soil property to assist the frost susceptibility of a soil has been the grain size distribution characteristic. This is probably related to the relative ease with which the laboratory grain size analysis can be performed. Johnson,[14] in his frost action literature review, compared the frost susceptibility criteria of different investigators (see Figure 3. Other authors[5,32] have made similar comparisons showing that

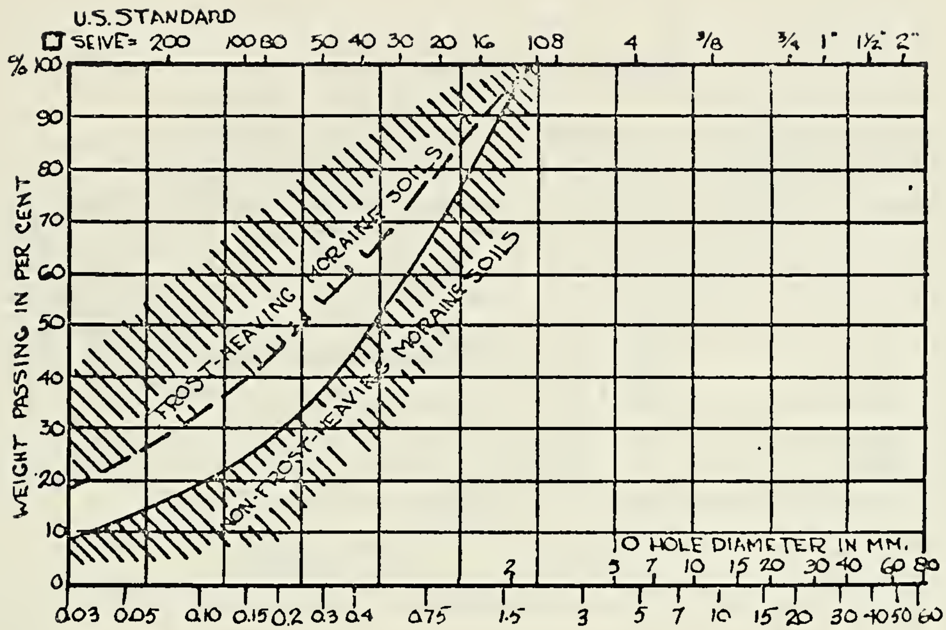

FIGURE 2. Limits Between Frost-Susceptible and Non-Frost-Susceptible Mixtures of Moraine Materials or Similar Mixtures

(after Beskow,[3] Fig. 66, p. 73)

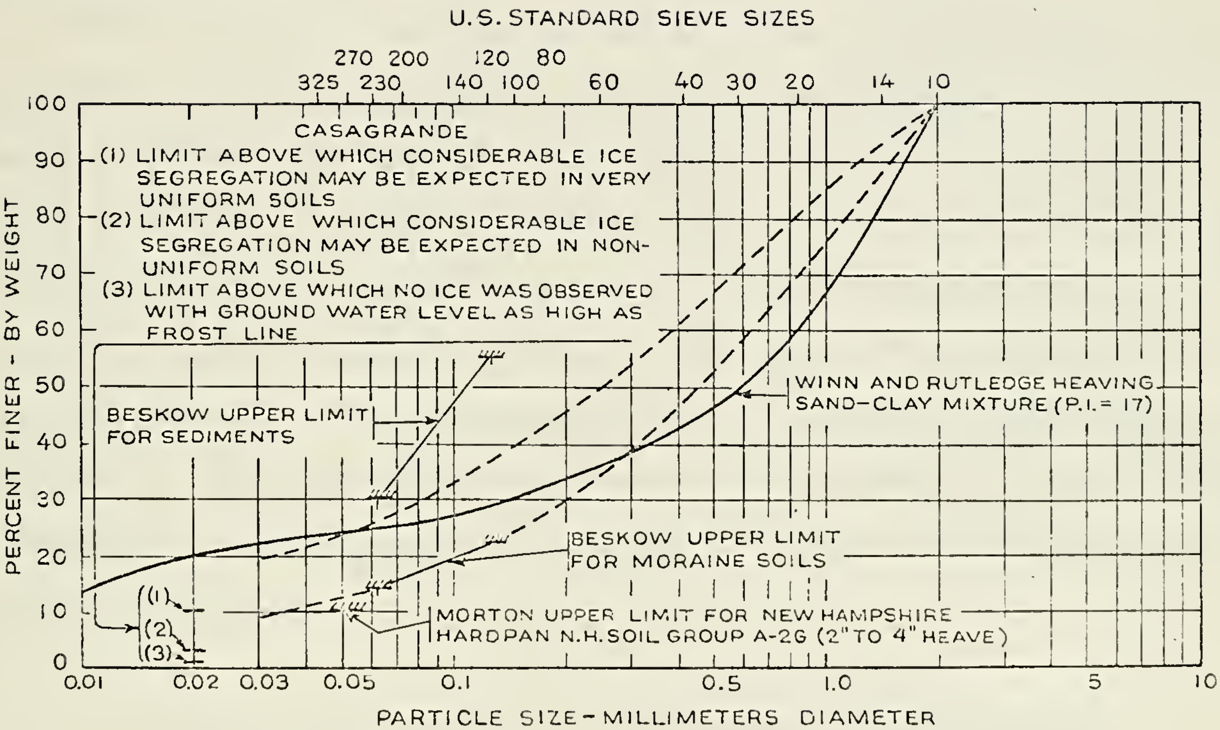

FIGURE 3. Comparison of Grain Size Limits for Frost-Heaving and Non-Frost-Heaving Soils by Different Investigators

(after Johnson,[14] Fig. 54, p. 64)

agreement does not exist on any one single criterion. Townsend and Csathy[32] reviewed ten criteria systems and concluded that the Casagrande Criteria appeared to be the most suitable for practical applications. They did, however, note that the grain size criteria had serious limitations. The Casagrande criteria have proven useful in identifying correctly about 85% of the frost-susceptible soils encountered.[33]

Frost Heave Rate Consideration

The frost heave rate serves as a guide to other influencing factors beyond the strict grain size criteria. Conditions such as temperature, rate of frost penetration, availability of water and surcharge load are also considered in judging the soil. The major objection to these criteria is the time required to conduct the test. Kaplar[16] describes the standard procedure used by the U. S. Army Corps of Engineers to evaluate the relative frost susceptibility of different soils. This procedure requires 15 to 20 days for the freezing period.[16] In accordance with the U. S. Army test procedure,[8,11] the following susceptibility classifications are assigned for rates of freezing between 1/4 and 1/2 inch per day:

Average Rate of Heave (mm/day)	Relative Frost Susceptibility Classification
0 - 0.5	Negligible
0.5 - 1.0	Very low
1.0 - 2.0	Low
2.0 - 4.0	Medium
4.0 - 8.0	High
Over 8.0	Very High

Kaplar[16] presents the results of all tests conducted by the U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory (CRREL) on natural soils using the standard test procedure he describes. Figure 4 is a summary showing groupings, according to soil types, of average rate of

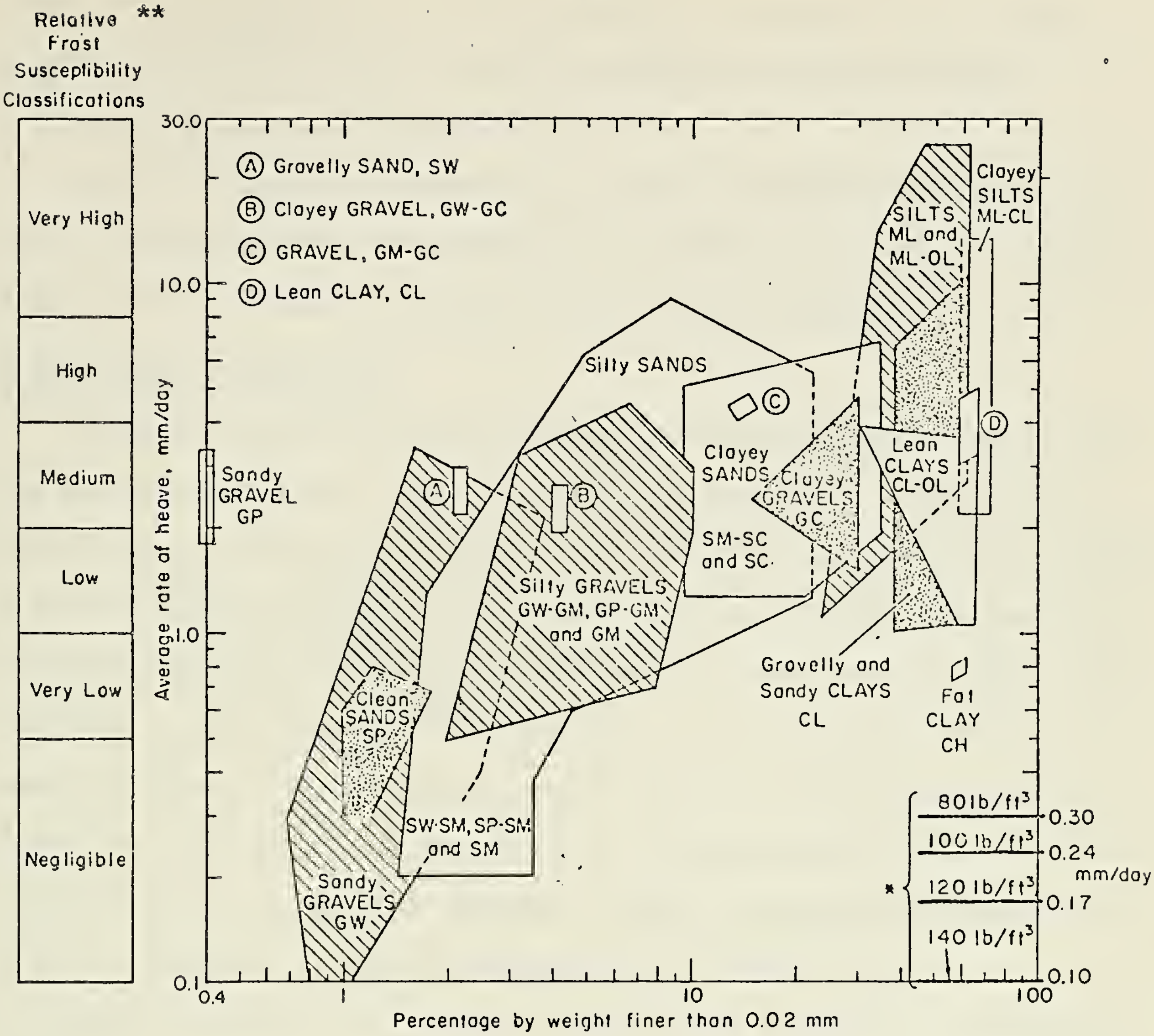

FIGURE 4. Summary of Average Rate of Heave vs. Percentage Finer Than 0.02 mm Size for Natural Soil Gradations (after Kaplar,[16] Fig. A2, p. 24).

NOTES:

*Indicated heave rate due to expansion in volume, if all original water in 100% saturated specimen were frozen, with rate of frost penetration 0.25 inch per day.

**For explanation of frost-susceptibility classifications, refer to text, page 8.

heave versus percentage finer than 0.02 mm soil gradations. It is readily apparent that no unique heave rate corresponds to any given percentage of material finer than 0.02 mm gradation.

Tests[15,17] have been conducted to evaluate the feasibility of shortening the U. S. Army's standard test procedure to 2-3 days. The current literature, however, does not indicate adoption of this revised procedure.

Thermodynamic Consideration

The phase-interface problem associated with the freezing of soil involves the thermodynamic aspects at the ice-water-soil interface. As discussed in the preceding sections and by others,[3,19,21,23,28] the basic problem associated with frost action (heaving) in soils is the increase in moisture content at the frost line which contributes to the growth of bulk ice (ice lenses) within the soil. Investigations[17,18,21] have shown that, among other things, the amount of heave (ice growth) can be related to the penetration rate of the frost line. Penner[21,22] has shown that if the penetration rate of the frost line is fast enough, the soil moisture is frozen *in situ* and the amount of heave is related only to the volume expansion of water to ice.

Everett[9] and Williams[35] along with others have viewed frost action from an equilibrium thermodynamic point of view. Everett[9] views the basic problem as one relating to the growth of a crystal which is subjected to an external constraint, i.e. ice crystal within the soil pores. The chemical potential of a small crystal immersed in, and in equilibrium with, a fluid subjected to a hydrostatic pressure P_h may be expressed as:[9]

$$E_c = E_c(P_h) + v^s \frac{d(T_s A)}{dV} \qquad (1)$$

where

E_c = chemical potential - FL

$E_c(P_h)$ = chemical potential of bulk solid at hydrostatic pressure P_h - FL

v^S = molar volume of solid (molecular weight/specific gravity of solid) - L^3

A = area of interface - L^2

V = total volume of solid - L^3

T_s = surface tension between solid and liquid - FL^{-1}

Assuming T_s is independent of V, then

$$E_c = E_c(P_h) + v^S T_s \frac{dA}{dV} \qquad (2)$$

The difference between the chemical potential of a small crystal relative to that of the bulk solid can be related to the difference in internal pressures.[9]

$$E_c = E_c(P_h) - v^S(P_s - P_h) \qquad (3)$$

where:

P_s = internal pressure of crystal - FL^{-2}

P_h = internal pressure of bulk solid - FL^{-2}

Combining equations (2) and (3) yields the relationship between the difference in pressure (crystal to bulk solid) and crystal size.

$$P_s - P_h = T_s \frac{dA}{dV} \qquad (4)$$

In the case of water freezing to ice, the pressure difference between the ice and water phase is given by equation (4) which may be rewritten as:

$$P_i - P_w = T_{iw} \frac{dA}{dV} \qquad (5)$$

where:

P_i = internal pressure of ice - FL^{-2}

P_w = pressure of water - FL^{-2}

T_{iw} = surface tension ice-water - FL^{-1}

A = area of ice-water interface, i.e. surface area of ice crystal(s) - L^2

In the freezing of a soil, the pore water freezes to form ice. The size of the ice crystals, therefore, depends on the size of the pores in which they lie. The stresses developed at the ice-water interface are dependent on the pore size. The pressure condition at the frost line is therefore described by equation (5).

It is helpful in understanding the particular application of equation (5) to discuss the conditions within an element of soil subjected to freezing. Consider the saturated soil depicted in Figure 5(a). The initial pore water

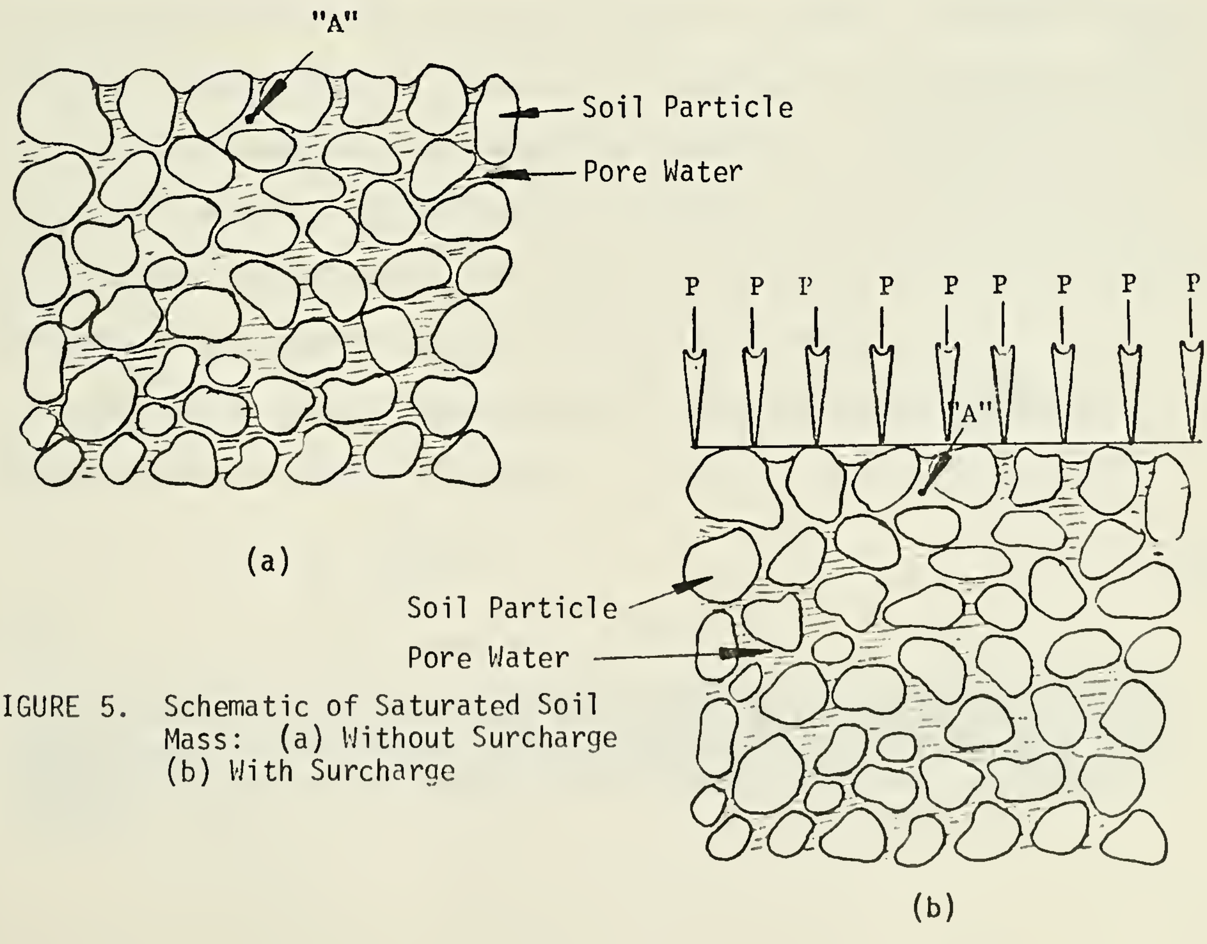

FIGURE 5. Schematic of Saturated Soil Mass: (a) Without Surcharge (b) With Surcharge

pressure is P_w and the surface is subjected to atmospheric pressure. Assume that the temperature is lowered to $0^{o}C$ and freezing is nucleated at point "A" within the pore water. As freezing proceeds, the ice crystal expands until the pore space is filled. At this point, ice growth will continue in one of two ways: (1) the ice will penetrate the pore necks, or (2) the soil particles will be pushed aside and upward. In order for the ice to enter the pore necks, P_i must satisfy equation (5) in which $\frac{dA}{dV}$ relates to the size of the pore neck. If this condition is not met and an adequate water supply remains in the system, then growth of the bulk ice crystal will continue due to the fact that the equilibrium conditions of equation (5) must be satisfied.

Consider, on the other hand, the condition depicted in Figure 5(b), where unlimited expansion of the bulk ice crystal is prevented. As the ice crystal grows, the internal pressure will increase until: (1) the restraining force (surcharge load) is overcome, or (2) the pressure required for the ice to penetrate into the necks between pores is reached. Provided freezing conditions prevail, the ice pressure P_i is related to the overburden pressure, i.e. the soil, water, ice mass above the frost line. Williams[35] reasons that, in order to control or reduce heaving, the frost line must penetrate downwards through the soil mass. For this to take place, the ice-water interface must pass through the pore necks within the soil matrix.

According to the well-known capillary equation (see Taylor[31]), air replaces water in a capillary when:

$$P_a - P_w = \frac{2T_{aw}{}^{*}}{r_c} \tag{6}$$

where:

P_a = pressure of air - FL^{-2}

*Strictly speaking, the right-hand term should be multiplied by a factor $\cos\theta$, where θ is the contact angle between the liquid and the wall of the capillary. The value is normally considered to be close to 1 for water in soils.

P_w = pressure of water - FL^{-2}

T_{aw} = surface tension air-water - FL^{-1}

r_c = radius of capillary - L

Williams[35,36] relates the penetration of the ice crystal into a water-filled pore neck with that of the penetration (intrusion) of air into the same pore neck. He reasons that the two pressures are proportional to the respective surface tensions. If, for simplicity, the pores of the soil are considered as cylindrical capillaries, then the interface dA/dV of equation (5) can be replaced by $2/r_c$ as in equation (6). Combining equations (5) and (6) gives the following:

$$\frac{P_i - P_w}{P_a - P_w} = \frac{T_{iw}}{T_{aw}} \qquad (7)$$

The values of T_{iw} and T_{aw} are known constants and are equal to T_{iw} = 30.5 dynes/cm; T_{aw} varies from 72.75 dynes/cm at 20°C to 75.6 dynes/cm at 0°C.* Williams, therefore, concludes that if the value of $P_a - P_w$ can be easily measured, then the value of $P_i - P_w$ can be predicted which will result in a penetrating frost line. Williams[35,37] proposes the use of an apparatus similar to that described in Chapter III of this thesis to determine the air-intrusion value $P_a - P_w$. He also presents sample calculations depicting the use of the air-intrusion value to determine the depth at which a given soil will not be frost-susceptible and heave will be halted.

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*Everett[9] points out that the value of surface tension ice to water is unreliable as estimates cover the range of 10-40 dynes/cm. Williams[35,37] assumes the value 30.5 dynes/cm.

CHAPTER III

TESTING PROGRAM, MATERIALS AND METHODS

General Comments

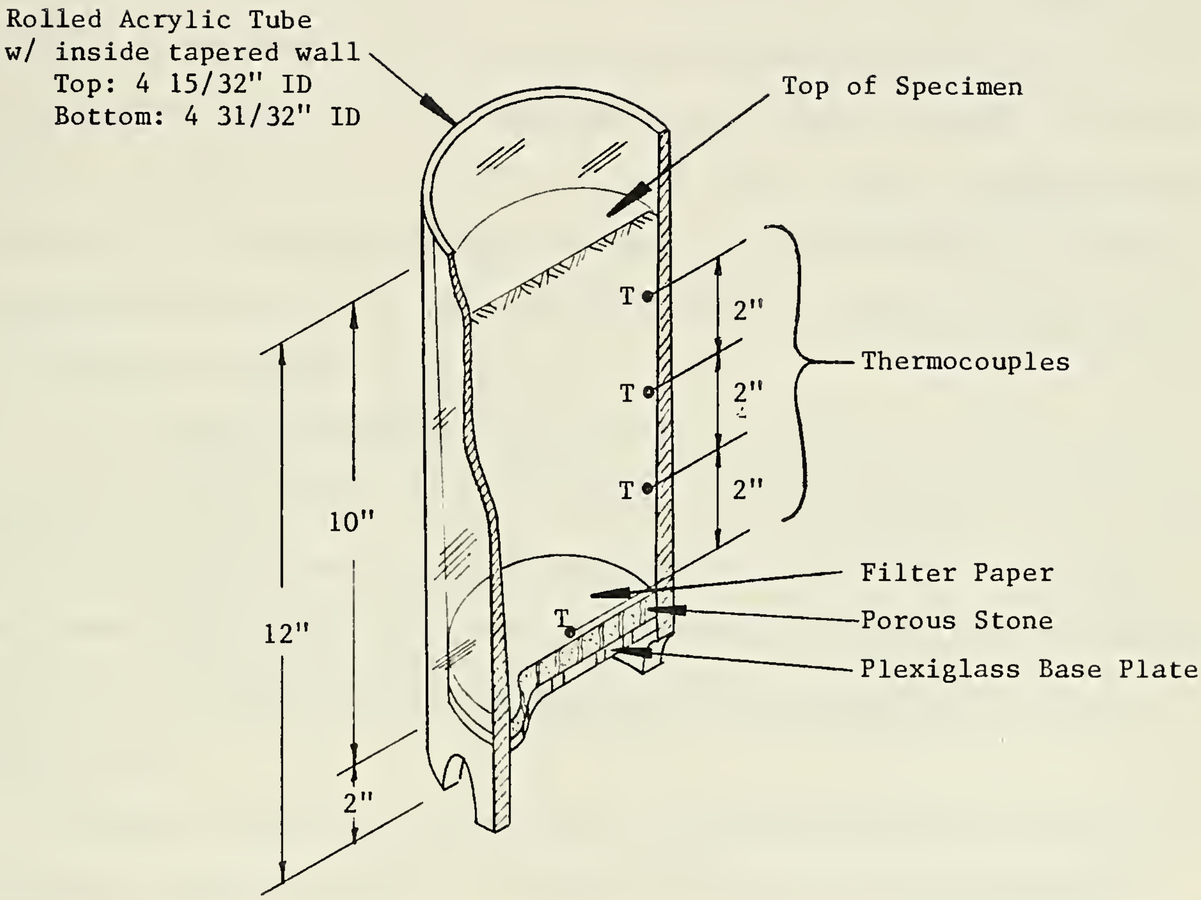
The testing program undertaken in this investigation consisted of preparing standard samples using Ottawa Sand of different grain size gradations. Each different specimen was subjected to variable freezing conditions in an open system to evaluate the relative frost susceptibility of each specimen. Air-intrusion values were obtained for each specimen. In obtaining these values, the effect of initial moisture content of the specimen on the air-intrusion value was investigated. An attempt was made to calculate the surcharge pressure required to prevent heave by use of the air-intrusion value. The effectiveness of the calculated surcharge was verified by freezing a loaded specimen in the freezing cell.

Freezing Cell

The soil freezing cell consists of a slightly tapered, vertical inner wall, rolled Acrylic tube. The tube is 12 inches (30.5 cm) in height with a porous stone base supported 2 inches (5.08 cm) from the bottom by a plexiglass base plate as shown in Figure 6. This allows a maximum specimen height of 10 inches (25.4 cm). The cell is instrumented with four thermocouples, one at the porous stone base and the remaining three placed at two-inch intervals up the vertical side wall of the cell.

Insulating Cabinet and Water Reservoir

The freezing test procedure required that the test specimens be initially cooled to a temperature of $4^{\circ}C$. The freezing was to be conducted in an open system whereby the water at the base of the specimen would remain at $4^{\circ}C$ while the freezing temperature would be applied to the top of the specimen.



NOTE:

Design of freezing cell simular in concept to cell used by U.S. Army Cold Regions Research and Engineering Laboratory and described by Kaplar (16,17).

Figure 6. Cross-section of freezing cell

The freezing temperature would be produced by placing the specimens in a walk-in type coldroom. This procedure, therefore, necessitated the use of an insulating cabinet to hold the specimens and keep the water reservoir at the desired temperature.

The insulating cabinet used in this investigation is shown schematically in Figure 7. The cabinet consists of an outer plywood box (29½" x 31¼" x 8") which supports and protects the styrofoam insulating box. Inside the insulating box is a sheet metal pan (24" x 24" x 3") which serves as the water reservoir and will accommodate six freezing cells. The underside of this pan is equipped with electric heat tape (ELECTROWRAP) and a thermostat-sensing bulb for temperature monitoring and control.

A more recent improvement has been the installation of a small circulating pump to continually circulate the water within the reservoir. This leads to a more uniform temperature distribution within the reservoir. A further improvement would be the replacement of the present thermostat with a thermostat which will enable the water temperature to be maintained at a more constant level.

The water level within the reservoir is checked daily with a dip stick and water is added as required. The water level was easily maintained to within 1/16 inch of the desired level throughout the duration of the experiment.

Temperature Measuring Equipment

The temperatures in soil specimens are measured by means of copper-constantan thermocouples placed in the soil at desired points. The thermal electromotive force produced by the thermocouples is measured electronically by instruments consisting of a ACROMAG (Model 345, Type T, copper-constantan) 25-channel thermocouple reference and Esterline Angus (model E1124E) multi-

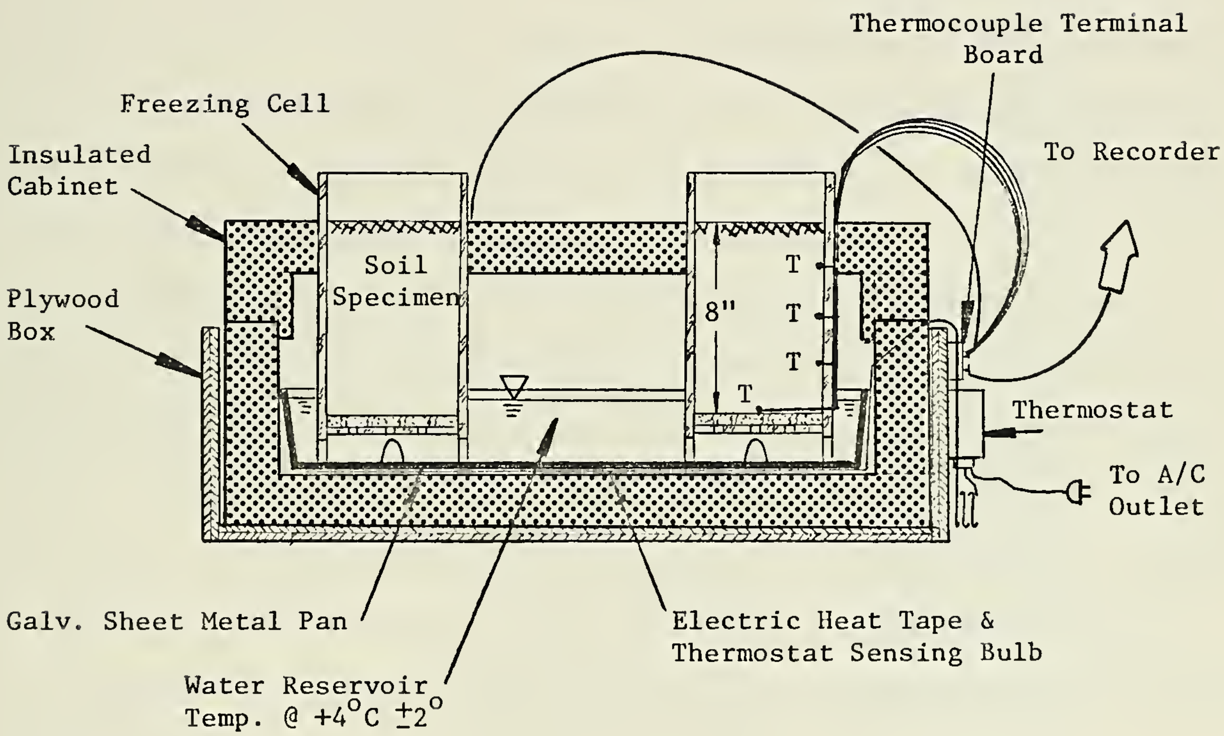


Figure 7. Details of Soil Insulating Cabinet and Water Reservoir

point recorder located immediately outside the coldroom. Temperatures can be read on the recorder to 0.10^{o}C accuracy. The recorder drive mechanism allows one reading to be taken every 54 seconds. The temperature of the cold room is controlled by a Honeywell Servoline Pneumatic Program Controller which continuously measures, records and controls the temperature of the coldroom at the desired level. A check was maintained on the coldroom temperature by means of a thermocouple inserted into a 500 ml beaker filled with Ethylene Gycol. The glycol dampens out any temperature fluctuations occurring in the coldroom resulting from normal operation of the cooling system. This temperature reading was continuously recorded by the Esterline Angus Recorder along with all other thermocouple readings. The controlling and recording equipment is placed directly outside the coldroom as shown in Plate 1.

The thermocouples used in this investigation were made up of Thermo Electric nylon insulated copper-constantan, thermocouple wire (NN24T). The measuring junction (thermocouple) was formed by the use of a QUIKTIP thermocouple pressure connector. This enabled all junctions to be uniform in size and shape. The terminal blocks used on the outside of the insulating cabinet consisted of standard terminal blocks with copper and constantan terminal lugs inserted in the appropriate terminal to insure continuity in each thermocouple circuit.

Air-Intrusion Test Apparatus

The air-intrusion apparatus consists essentially of a Tempe Pressure Cell connected to a regulated compressed air source and a drainage system with a calibrated burette to measure the water drainage from the specimen. The apparatus is shown in Plates 2 and 3 with a cross-sectional view of the Tempe Pressure Cell and soil specimen shown in Figure 8. Two different ceramic plates were used in the investigation depending upon the estimated air-

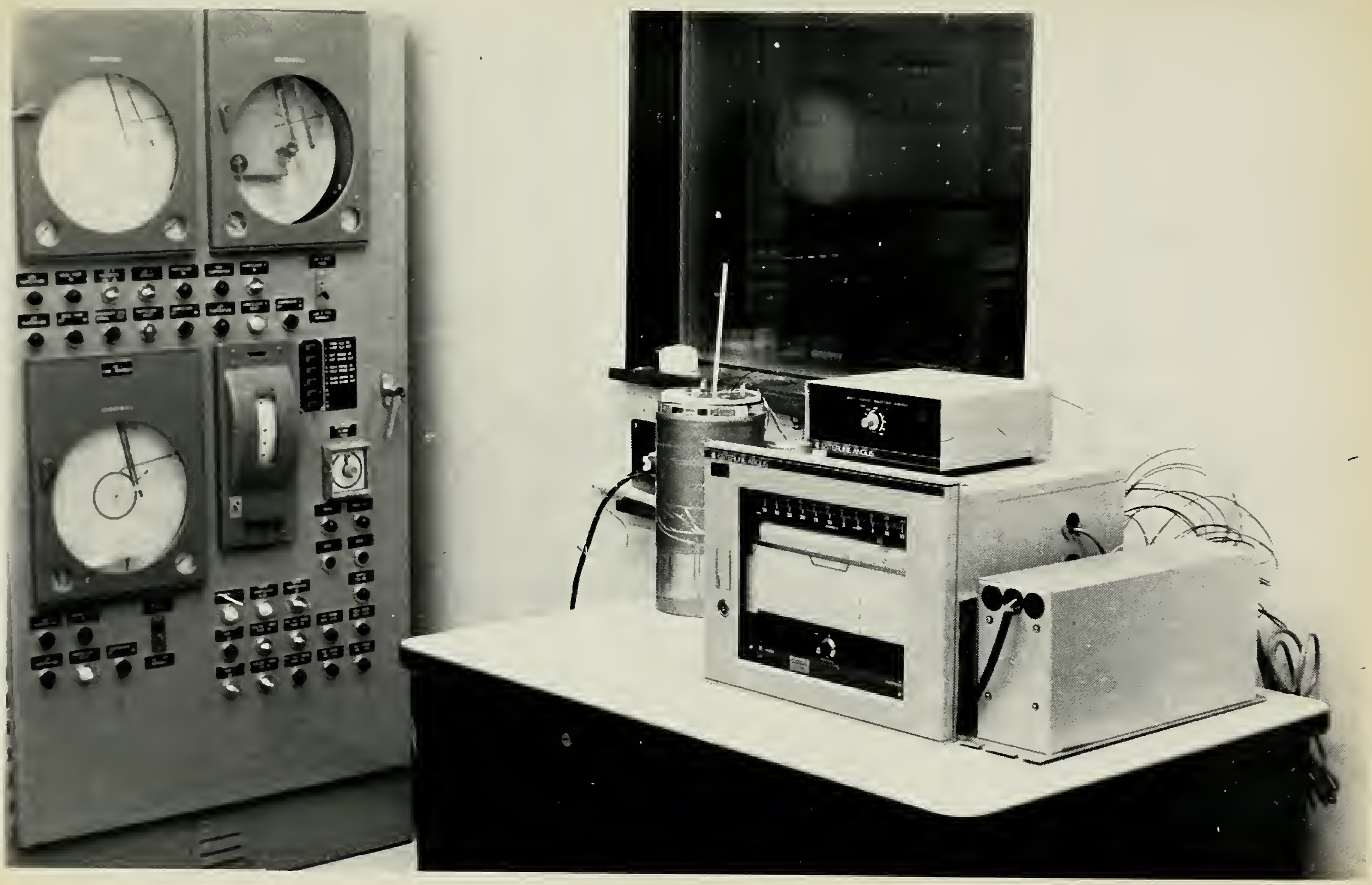


PLATE 1 - Temperature Measuring Equipment for Use With Thermo-
couples and Controlling Equipment for Coldroom

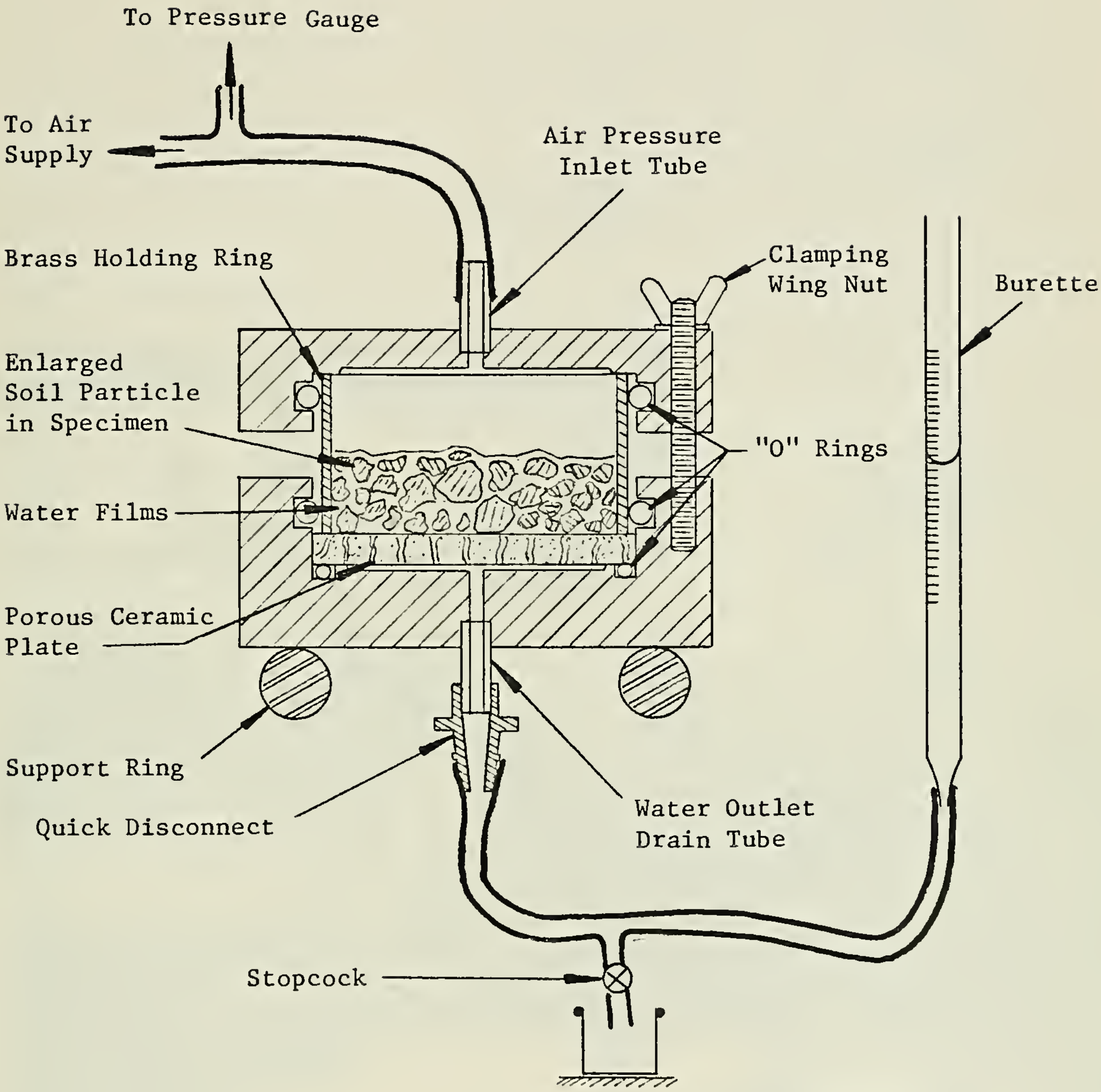


Figure 8. Air -Intrusion test apparatus showing cross-section of TEMPE pressure cell and drainage measuring system

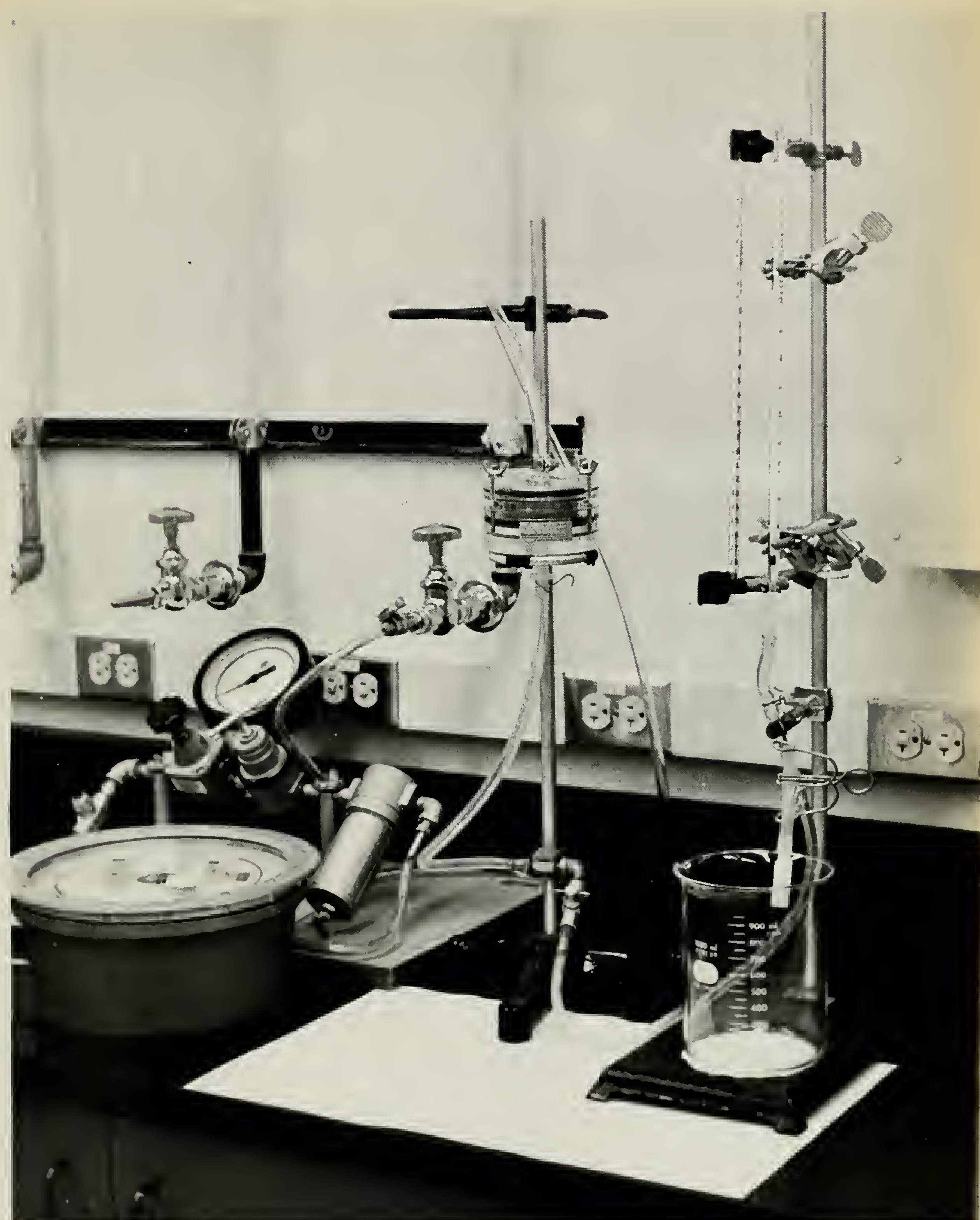


PLATE 2 - Air-Intrusion Apparatus

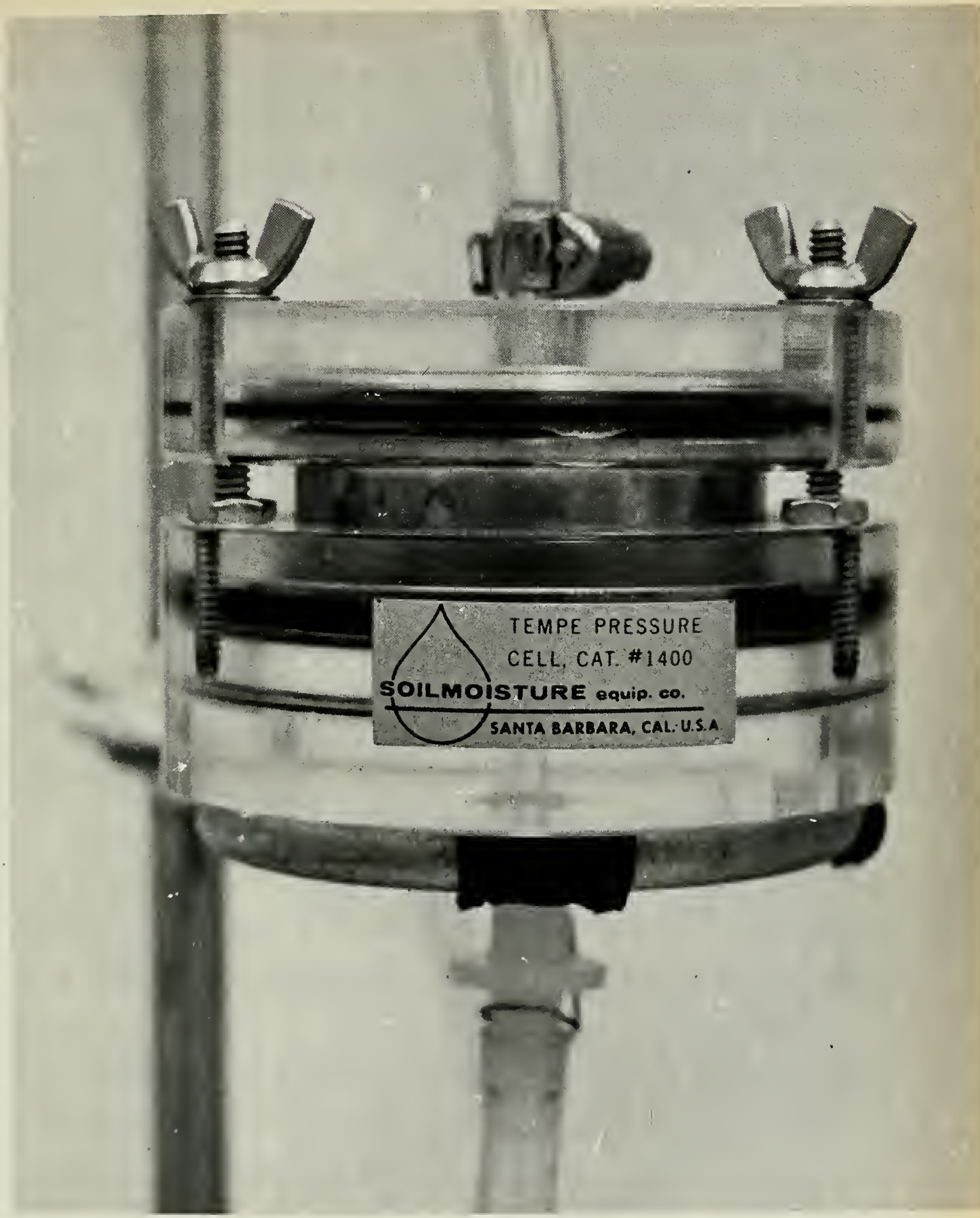


PLATE 3 - Tempe Pressure Cell

intrusion value. One ceramic plate (1/4-bar) had a bubbling pressure of 3.2 psi with a flow rate of approximately 1,200 $ml/hr/cm^2$ whereas the other plate (1-bar) had a bubbling pressure in excess of 20.0 psi and a flow rate of 4 $ml/hr/cm^2$. As pointed out by Williams,[35] the larger flow rate is desirable in order not to interfere with the free drainage of the specimen. The high bubbling pressure is desired in order to restrict the passage of air into the drainage system. The two different ceramic stones were used by this investigator because a 1-bar high flow rate plate was not available during the time of investigation. A 1-bar high flow rate porous ceramic plate is commercially available and should be obtained if the use of the Tempe Pressure Cell is to be continued. The other alternative is to incorporated the use of a membrane as used by Williams.

Soil Specimens

Four commercially available gradations of Ottawa Sand were obtained for use in this investigation. A grain size distribution was obtained for each specimen by a combined sieve and hydrometer analysis and compared with grain size criteria for frost susceptible soils. Figure 9 shows the respective gradations and comparison with criteria. As none of the specimens were close to critical values, three blends were prepared which would more closely bracket the criteria. These gradations are also shown in Figure 9.

Standard Proctor compaction tests (25 blows, 5.5 lb hammer, 12.0 in drop) American Society for Testing and Materials (ASTM) Designation D698-70 were performed on each different specimen gradation to determine an optimum moisture content. The results are shown in Figure 10. In preparation for the freezing test, each specimen is molded in the freezing cell at its optimum moisture content.

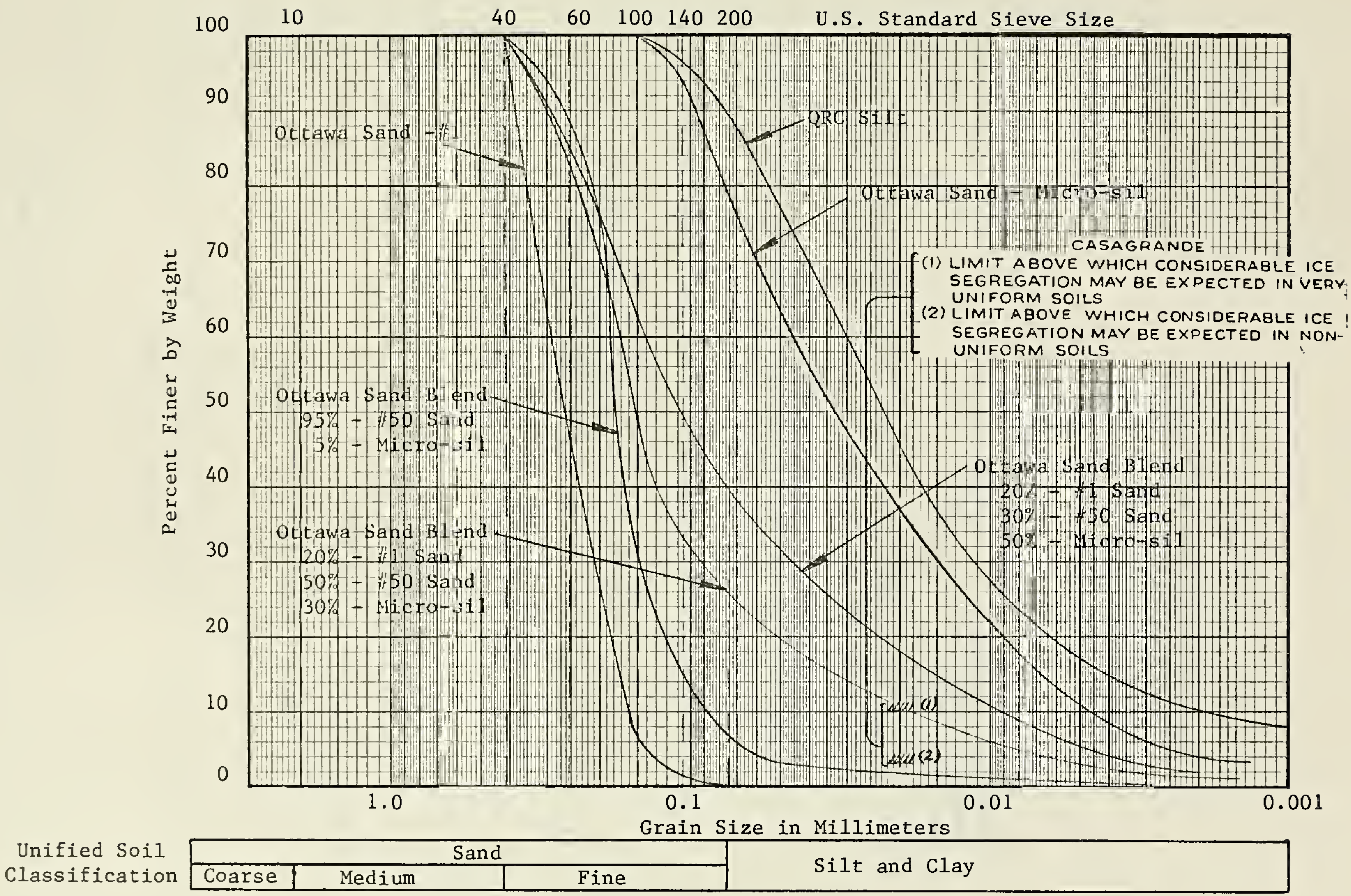


Figure 9. Soil Gradation Curves

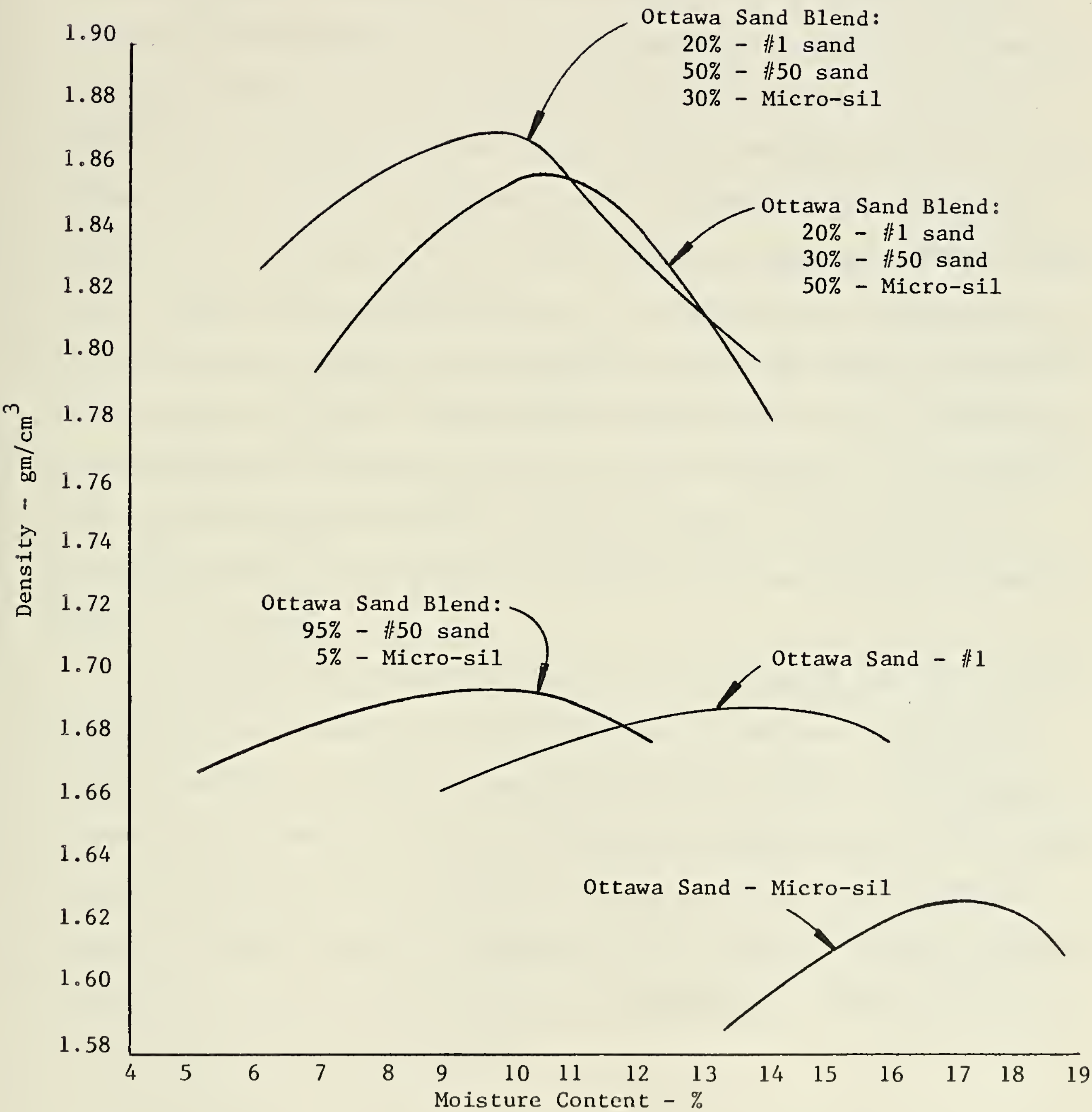


Figure 10. Density vs Moisture Content

Preparation of Specimens

Soil specimens for the freezing/heaving test were molded in a slightly tapered 12-inch high rolled Acrylic tube as described under Freezing Cell. The inner surface of the tube is first lubricated with silicone grease to minimize friction between the cell and specimen when heave takes place during freezing. Quantities of each specimen were prepared at their respective optimum moisture contents, placed in plastic bags, sealed and placed in a cold storage area at $+4^{o}C$ for a minimum period of 24 hours. The specimens were then molded in the freezing cells with a compactive energy equivalent to that of the standard Procter compaction test. The freezing cells containing the specimens were then placed in the insulating cabinet and allowed to cold soak for a minimum of 24 hours at the coldroom temperature of $+4^{o}C$. Temperatures of the specimen are recorded to insure a uniform temperature of the specimen prior to starting the freeze cycle. The water level in the reservoir is maintained at about 3/8 inch above the bottom of the specimen (top of porous stone) at all times.

Soil specimens for the air-intrusion test are prepared from the dry state by adding the proper amount of distilled water to a measured weight of dry sample to produce a specimen at the desired moisture content. The prepared specimens are placed in air-tight containers and allowed to set at room temperature for a minimum period of 24 hours prior to testing. This allowed the specimens to obtain a uniform temperature and for the soil particles to absorb moisture. Prior to the actual testing, the specimen was remixed to insure a more uniform moisture distribution.

Freezing Test Procedure

Prior to freezing as noted under preparation of specimens, the specimens to be frozen are tempered for 24 hours at $+4^{o}C$ in the insulation cabinet.

This allows the sample to obtain a uniform temperature and to absorb water as required.

The level of the specimen surface below the top of the freezing cell rim is measured and recorded prior to lowering of the coldroom temperature to the desired freezing level. Once the coldroom temperature has obtained the desired level, nucleation of the soil water is initiated by seeding the surface of the specimen with a fine pulverized ice. Temperatures of the specimen are continually recorded throughout the freezing period. The height of the surface of the specimen is recorded periodically throughout the freezing period to record the amount of heave of each sample.

The specimens are gradually frozen from the top down for 72-80 hours. Cabinet, water and specimen temperatures are continuously recorded and heave measurements are usually recorded twice daily during the freezing period. At the end of the freeze period, the coldroom temperature is raised to +4^{O}C and the specimens are allowed to thaw. The thawing period is usually three days; however, temperatures are recorded three times a day until the temperature of the specimen has stabilized at about +4^{O}C. At this point, the thawing period is completed and another freezing period started. The specimens are not removed from the cabinet or disturbed in any way during the thawing period. The process is continued until three freeze cycles have been completed. At this point, the specimens are thawed and removed from the freezing cells. In the thaw periods, natural drainage from the soil specimen to the reservoir is permitted. Drainage was visually observed taking place during the thaw cycle.

<u>Air-Intrusion Test Procedure</u>

The air-intrusion test is performed by placing the moist soil specimen in the pressure cell and applying controlled air pressure to the cell in stages and measuring the drainage from the cell. The apparatus is shown in

Figure 8 and Plates 2 and 3.

To prepare the Tempe Pressure Cell for operation, the porous ceramic plate is fully saturated and deaerated. This is accomplished by placing the ceramic plate in a vacuum desiccator which is filled with distilled water and boiled under a vacuum. The drain connection of the cell is closed and the bottom portion of the cell is filled with distilled water. The ceramic plate is then replaced into the bottom of the cell. The O-ring and brass holding ring are also replaced. The cell is then placed on the support stand and connected by use of a quick disconnect to the burette measuring system. Once the cell and drainage system are connected, the water level within the pressure cell is lowered to the top of the ceramic plate by opening the stop-cock. It is important during the above operation that care is taken to insure that no air bubbles are entrapped in the drainage system between the ceramic plate and the top of the meniscus in the burette.

The soil specimen at the desired moisture content is placed into the holding ring to a depth of 1.5 cm. The specimen is placed in three layers and each layer is compacted by hand rodding to a firm density. The top portion of the cell is installed and secured with the three wing nuts.

Regulated compressed air is then applied to the cell in a series of equal pressure increments at equal time intervals until the air-intrusion pressure has been exceeded. The cumulative drainage of water from the specimen is measured and recorded at each time interval. A typical test data sheet is shown in Appendix A.

The air-intrusion pressure is obtained by plotting the cumulative amount of drainage versus elapsed time and pressure versus elapsed time. The air-intrusion pressure is that pressure which is applied to the specimen when the drainage curve shows an acceleration in drainage. See Appendix A for sample curves.

CHAPTER IV

RESULTS AND DISCUSSION

Frost Heave Tests

A series of freezing tests were performed using Ottawa Sand. As the natural (commercially available) gradations were not as desired, three blended samples were prepared for use. Two unaltered samples were also used. The gradations of the five samples used in the investigation program are shown in Figure 9. The samples were subjected to mineralogical analysis by X-ray diffraction techniques. This analysis showed the samples to be predominantly quartz with some low temperature plagioclase feldspar.

Table I presents the results of heave tests performed on the specimens at three different surface temperatures.

TABLE I

COMPARISON OF HEAVE RATE AND SURFACE TEMPERATURES*

Specimen**	Average Heave Rate in mm/Day		
	Room Temperature $-2.5^{\circ}C$	Room Temperature $-5.0^{\circ}C$	Room Temperature $-10^{\circ}C$
#1 Sand	0	0	0
Blend 95-5	0	0	0
Blend 20-50-30	1.0	3.0	1.0
Blend 20-30-50	1.6	3.3	1.6
Micro-sil	5.0	4.0	3.0

*Based upon three-cycle freeze-thaw test procedure with constant freeze period of 72 hours.

**Refer to Figure 9 for complete specimen descriptions.

Figures 11 through 13 present plots of average heave and frost penetration data for the three frost susceptible soils (Micro-sil, Blend 20-30-50 and 20-50-30) at the three different freezing test temperatures. Figure 11(a)

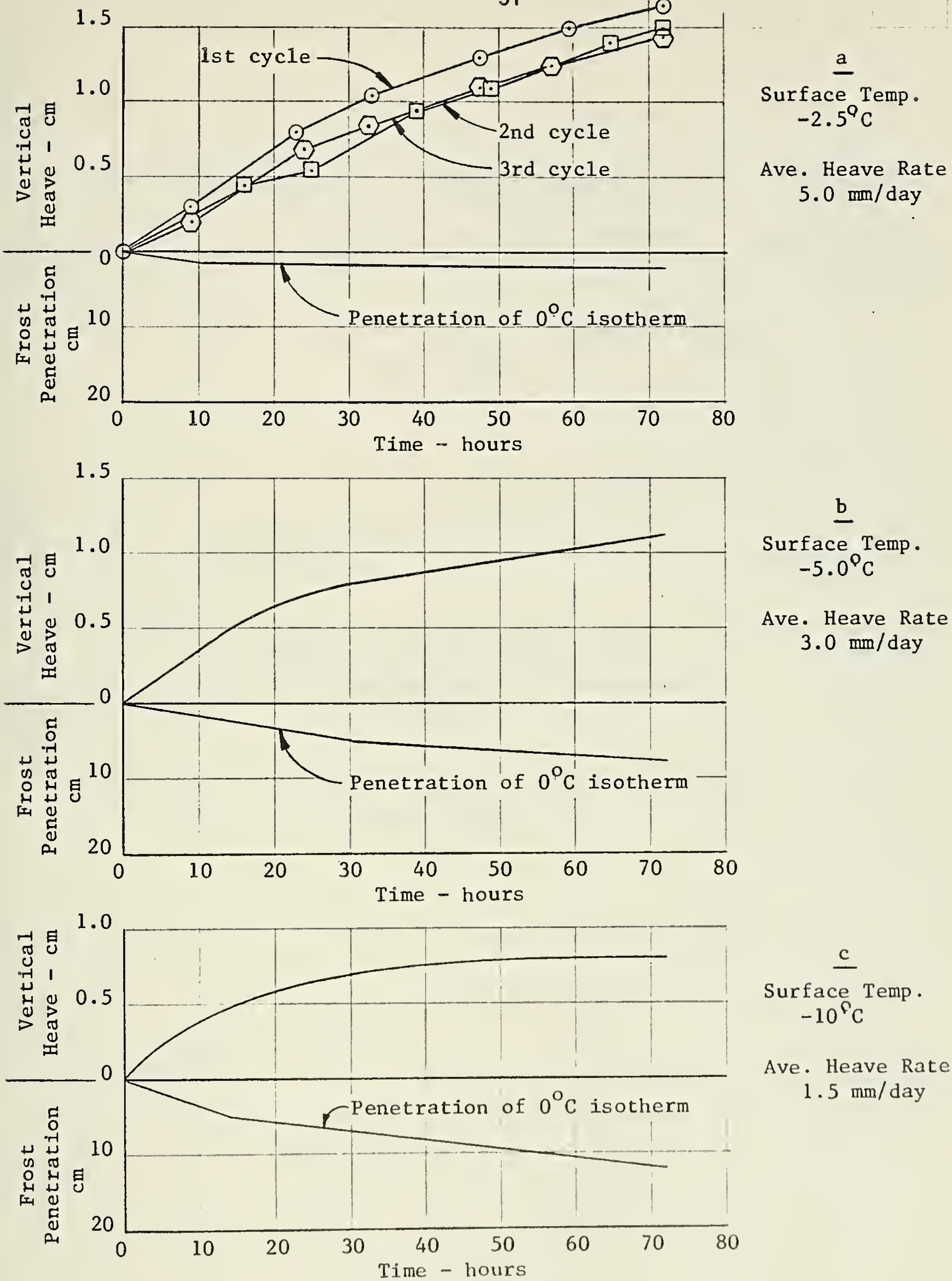


Figure 11. Heave and Frost Penetration Data for Micro-sil

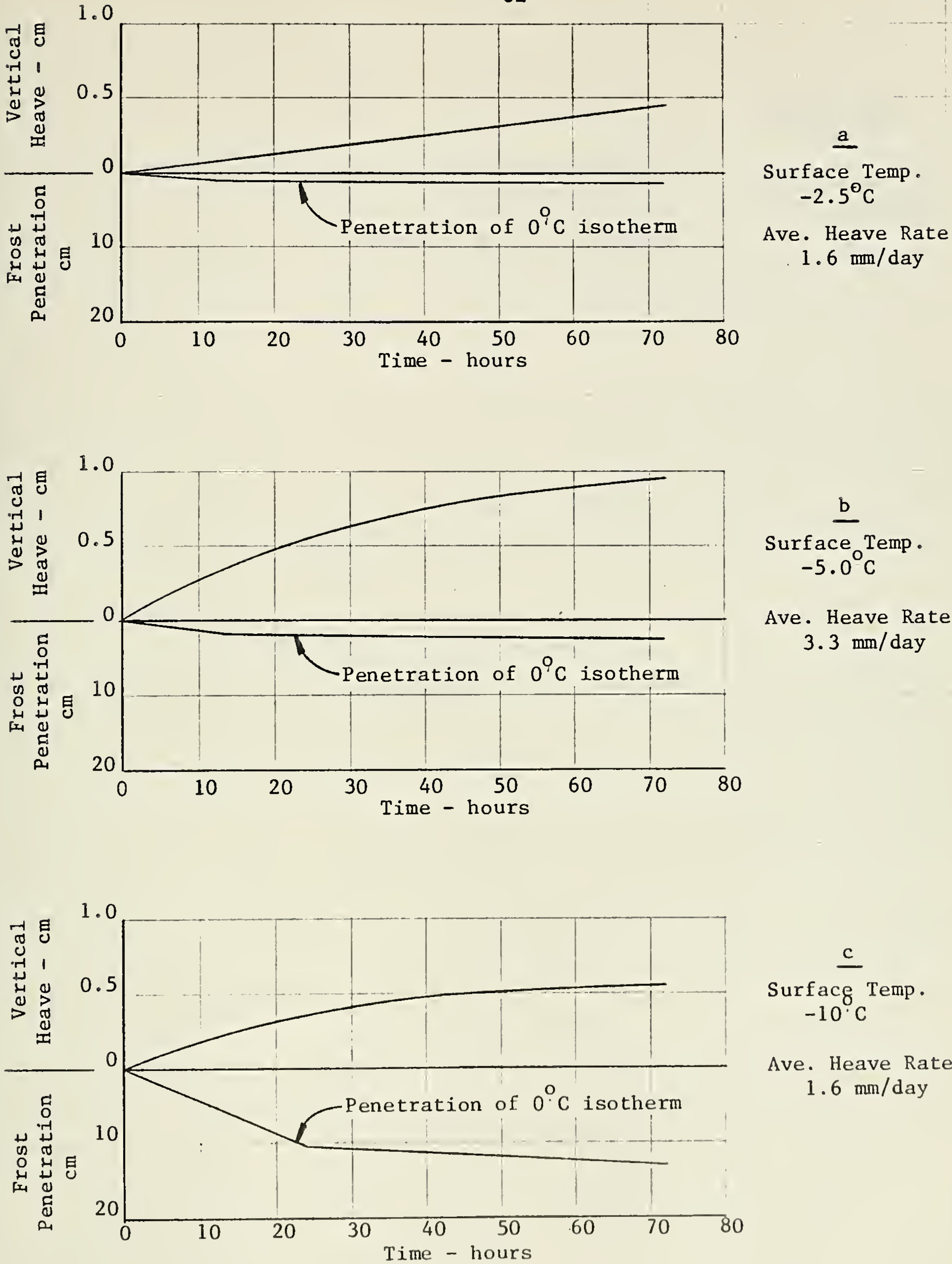


Figure 12. Heave and Frost Penetration Data for Blend 20-30-50

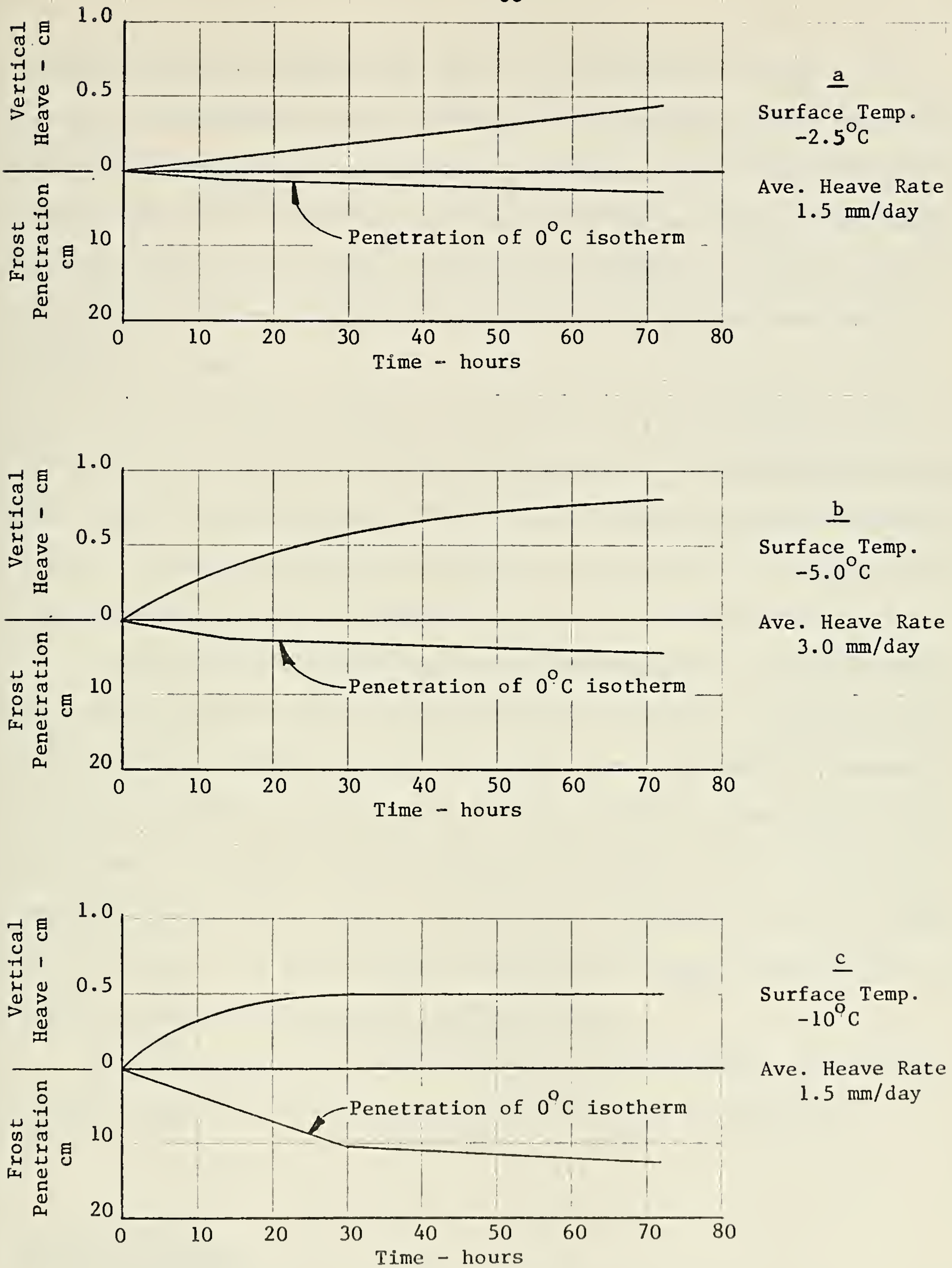


Figure 13. Heave and Frost Penetration Data for Blend 20-50-30

presents heave vs. time data for each of the three freeze cycles. It is noted that the amount of heave decreases after the initial cycle and remains relatively constant for the subsequent two cycles. The frost penetration vs. time plots, on the other hand, coincide for all three cycles. This observation was noted for all frost-susceptible soils tested. In order to simplify the remaining plots in Figures 11 through 13, only average heave data is plotted vs. time.

It is the author's opinion that the cause of this reduction in the rate of heave can be attributed to the rearrangement of the soil particles following the initial freeze-thaw cycle. The soil matrix (pore size) is altered which results in changed conditions relative to moisture flow, ice crystal pressure, pore arrangement, etc. which affect the growth of ice within the soil.

The results of the frost heave tests indicate that, of the five specimens tested, the micro-sil is the most frost-susceptible followed by blend 20-30-50 and blend 20-50-30. This is reasonable as the micro-sil contains a high percentage of fine particles. Refer to Figure 9 Both the #1 sand and blend 95-5 showed no sign of heaving in any tests. This is also to be expected because, when comparing the specimen gradation with frost susceptibility criteria, one finds neither specimen has an appreciable amount of fine particles below the #200 sieve (0.074 mm) size.

The cause of the reduction in heave shown by two blends 20-30-50 and 20-50-30 under the slow frost penetration conditions is uncertain.

Air-Intrusion Test

The investigation of the use of the air-intrusion value proceeded along three avenues: (1) obtaining the air-intrusion value for each different

sample investigated in the freeze test; (2) evaluating the air-intrusion value as a function of initial moisture content of the specimen tested; and (3) assessing the practical utility of the air-intrusion test. Williams[34] found that the most satisfactory procedure for preparing the soil specimen was to boil the material and place it into the apparatus in a homogenous slurry. When this procedure was followed by this author, visual inspection of the tested specimen revealed some segregation of the fines to the top of the specimen. This is attributed to an excessive amount of water in the boiled slurry. Tests were, therefore, conducted to evaluate the effect of initial moisture content of the specimen on the resulting air-intrusion value.

Air-intrusion tests were performed with three samples using varying initial moisture contents. Figures 14 through 16 present the results of these tests. It is to be noted that a slight reduction in the air-intrusion value is obtained with increased moisture content. In the case of the micro-sil, the value obtained using the slurry is about half the value obtained using lower moisture contents. This is attributed to the segregation problem noted above. Table II summarizes the air-intrusion values for the five samples tested.

TABLE II
SUMMARY OF AIR-INTRUSION VALUES

Specimen	Air-Intrusion Pressure - psi		
	High	Low	Average
#1	0.35	0.35	0.35
Blend 95-5	0.8	0.7	0.75
Blend 20-50-30	1.2	0.8	1.0
Blend 20-30-50	2.4	1.7	2.0
Micro-sil	3.6	2.5	3.1

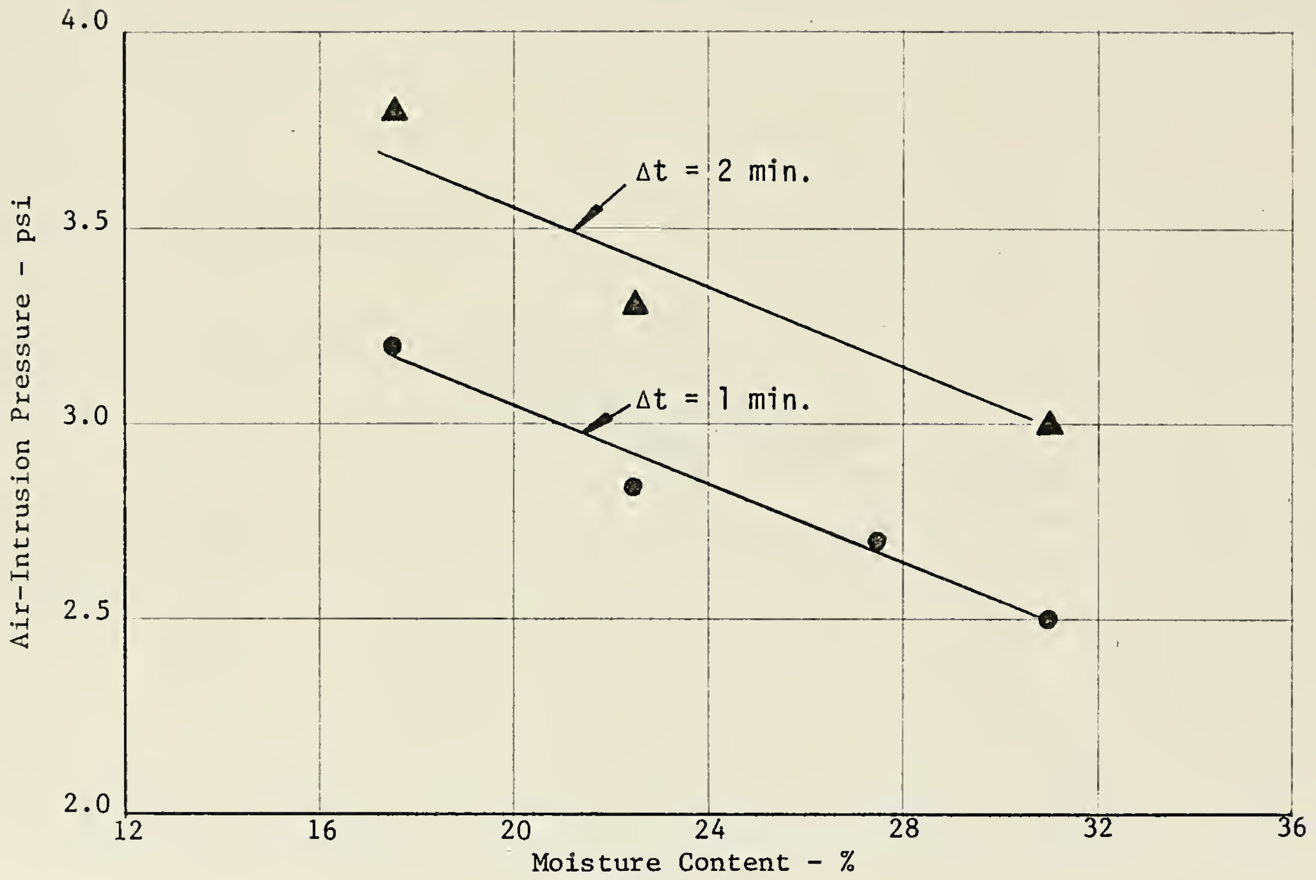


Figure 14. Air-Intrusion Pressure vs Moisture Content for Micro-sil

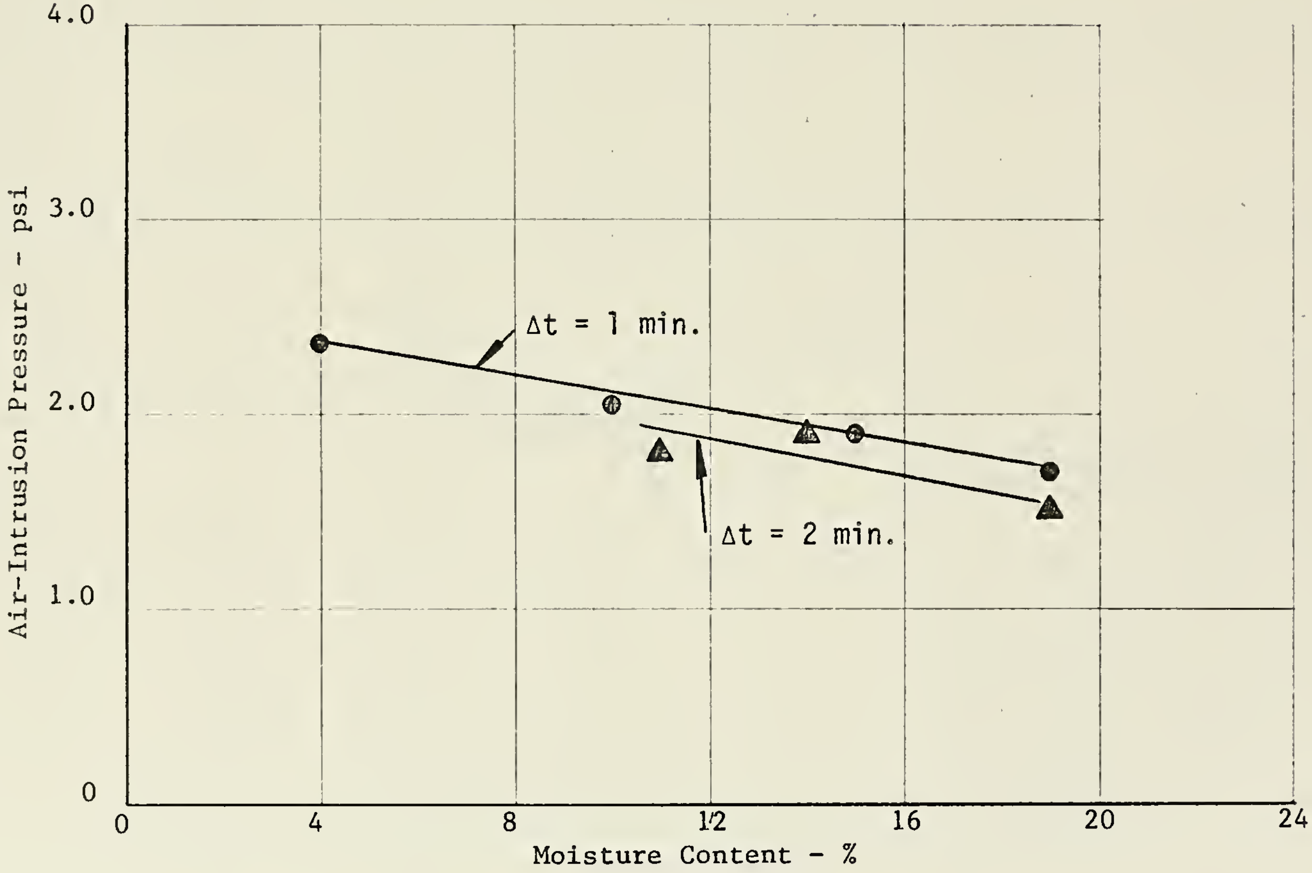


Figure 15. Air-Intrusion Pressure vs Moisture Content for Blend 20-30-50

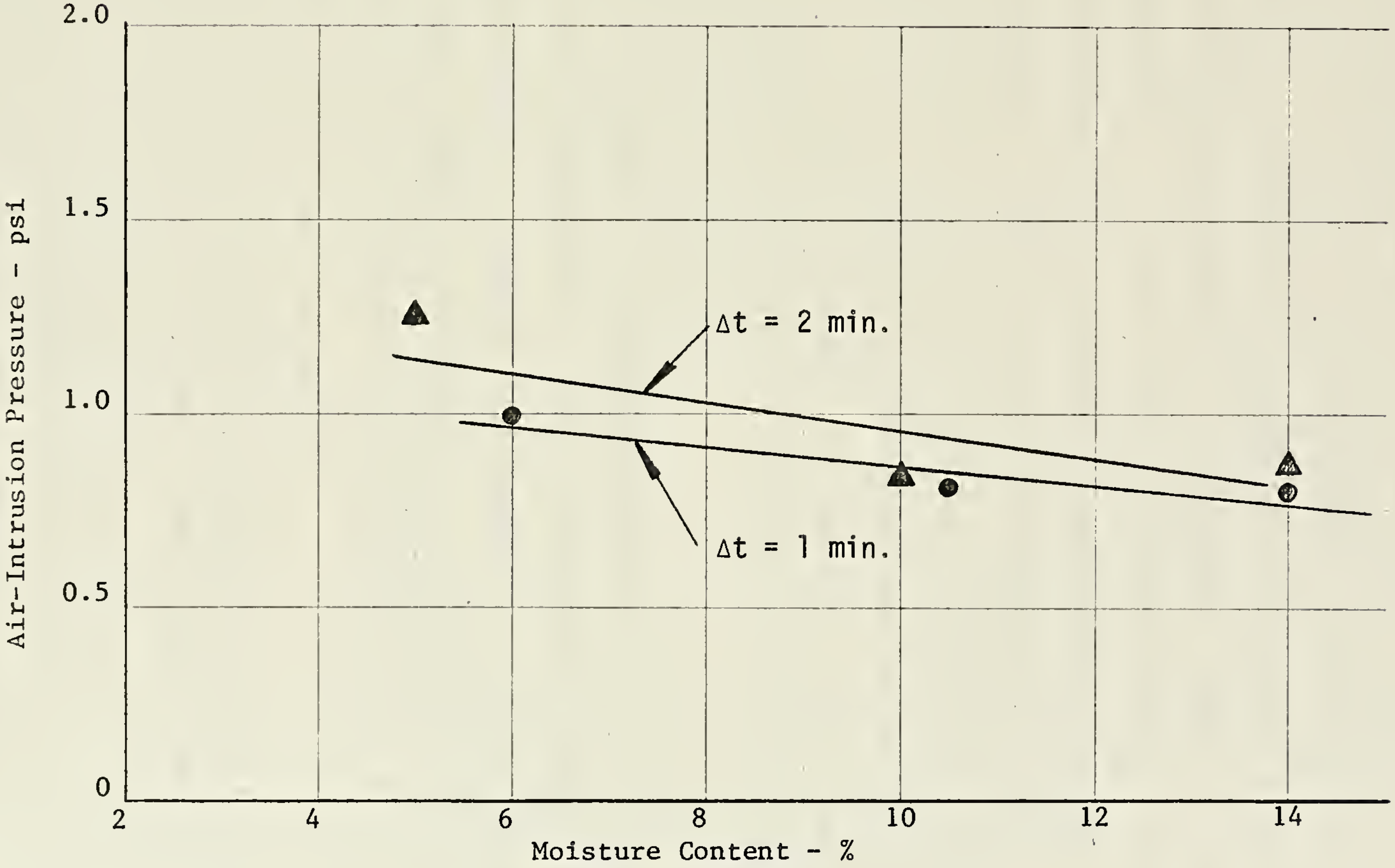
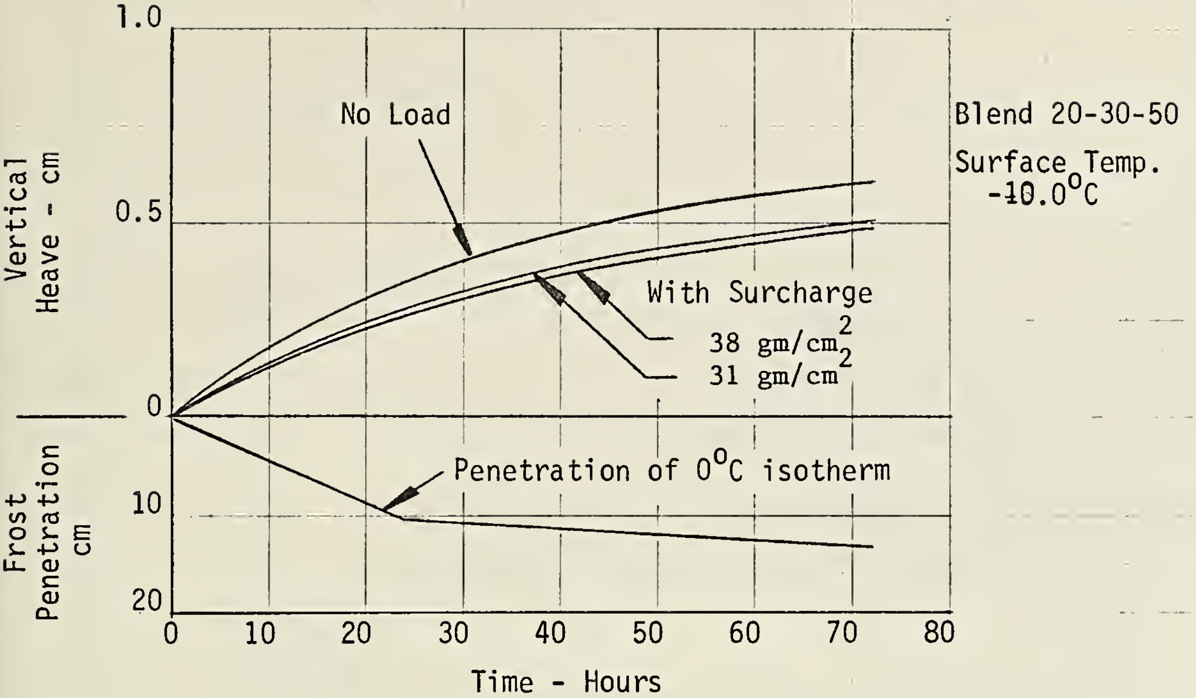


Figure 16. Air-Intrusion Pressure vs Moisture Content for Blend 20-50-30

Williams[35,36] expressed concern regarding the time involved in performing the air-intrusion test. His concern centered around the slow advance of the air/water interfaces into the soil with time under a constant $P_a - P_w$ value. This author could not find a maximum recommended time interval in which to perform the test; therefore, the investigation was extended to evaluate the air-intrusion value as a function of time duration. Figures 14 through 16 present these results. A slight increase in the air-intrusion value was noted with an increase in the time rate of application of pressure. This increase was greatest in the case of the fine material (micro-sil). The reason for this may be due to the fact that the adsorbed water around the small micro-sil particles will have to undergo shearing action during the process of flow. This is because this water possesses high viscosity due to its high molecular orientation on the micro-sil particles which possess high surface energy and/or specific volumes.

In this investigation, no appreciable change resulted from extending the test duration up to 40-60 minutes. This coincides with a time rate of 2 minutes between load applications. Tests were also performed at time intervals of 4 and 8 minutes; however, the results were inconclusive. The testing time for such tests was 1½ to 3 hours. Such long test periods tend to defeat the purpose of the indirect testing procedure.

In order to evaluate the practical application of the air-intrusion value, calculations were made to determine the surcharge load needed to stop heave in the freezing cell for two specimens. Calculations as outlined by Williams[35] were performed (see Appendix C). The specimens were molded in the freezing cells, the calculated surcharge stress applied and the cells subjected to freezing at a constant surface temperature. Figure 17 represents the resulting heave vs. time plots. It is apparent that heave action was not stopped as predicted. In evaluating the test and calculations, the author has



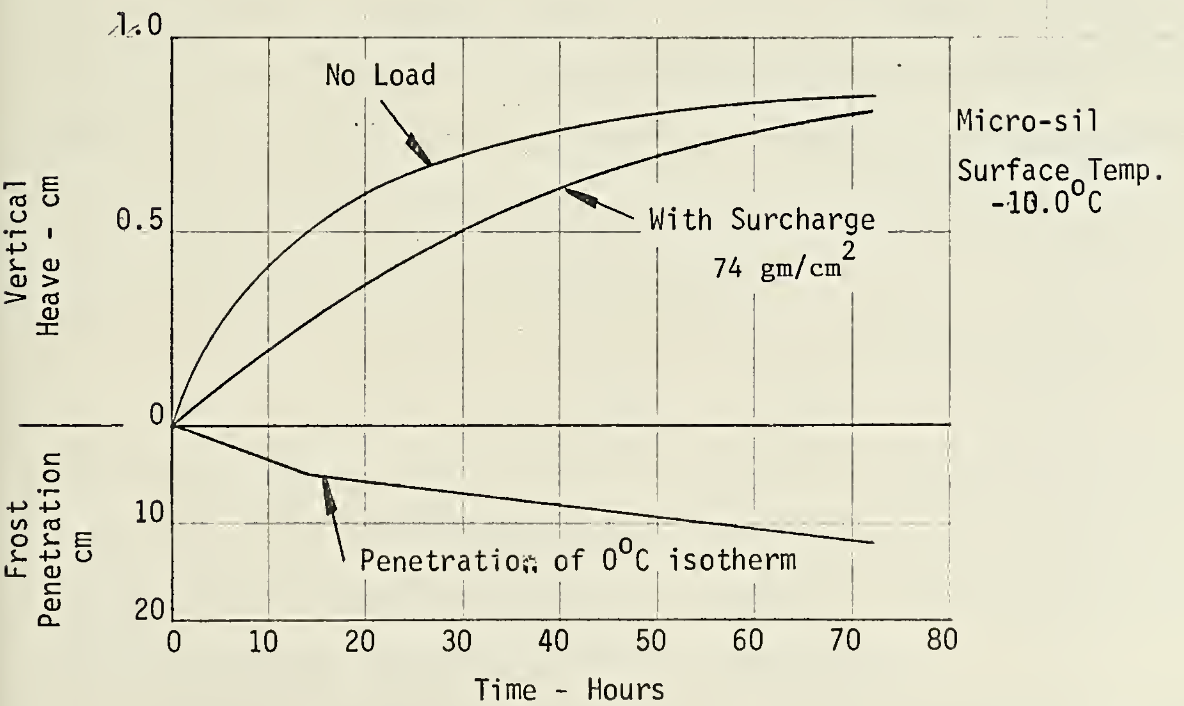


Figure 17. Heave and frost penetration data for loaded specimens of micro-sil and blend 20-30-50

re-evaluated the state of stress within the soil mass at the frost line.

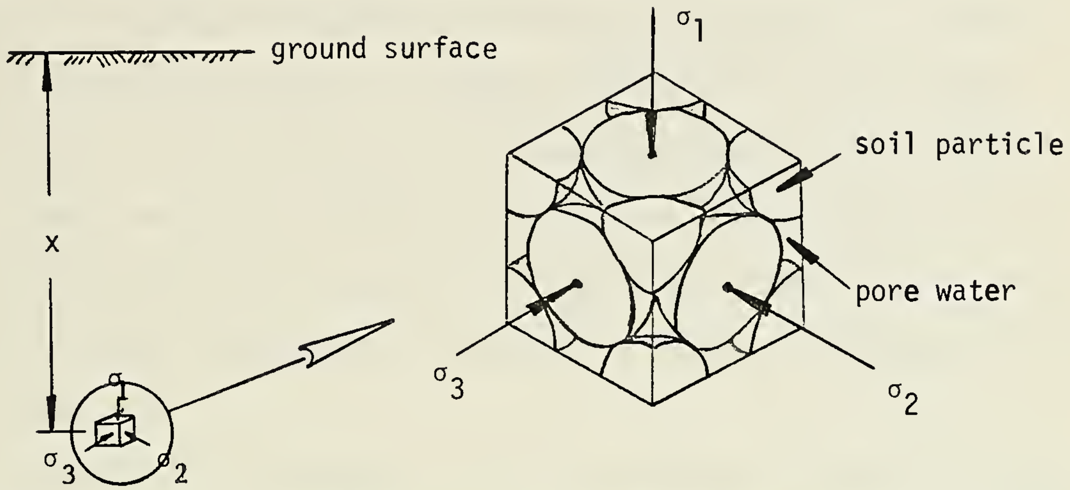


FIGURE 18. Schematic of Saturated Soil Element.

Consider the unfrozen, saturated soil element shown in Figure 18. It is well-known in Geotechnical Engineering that the soil element can be considered to be subjected to three principal stresses σ_1, σ_2 and σ_3 as shown. The average of these three stresses is known as the octahedral normal stress and can be considered a hydrostatic component.

$$\sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{8}$$

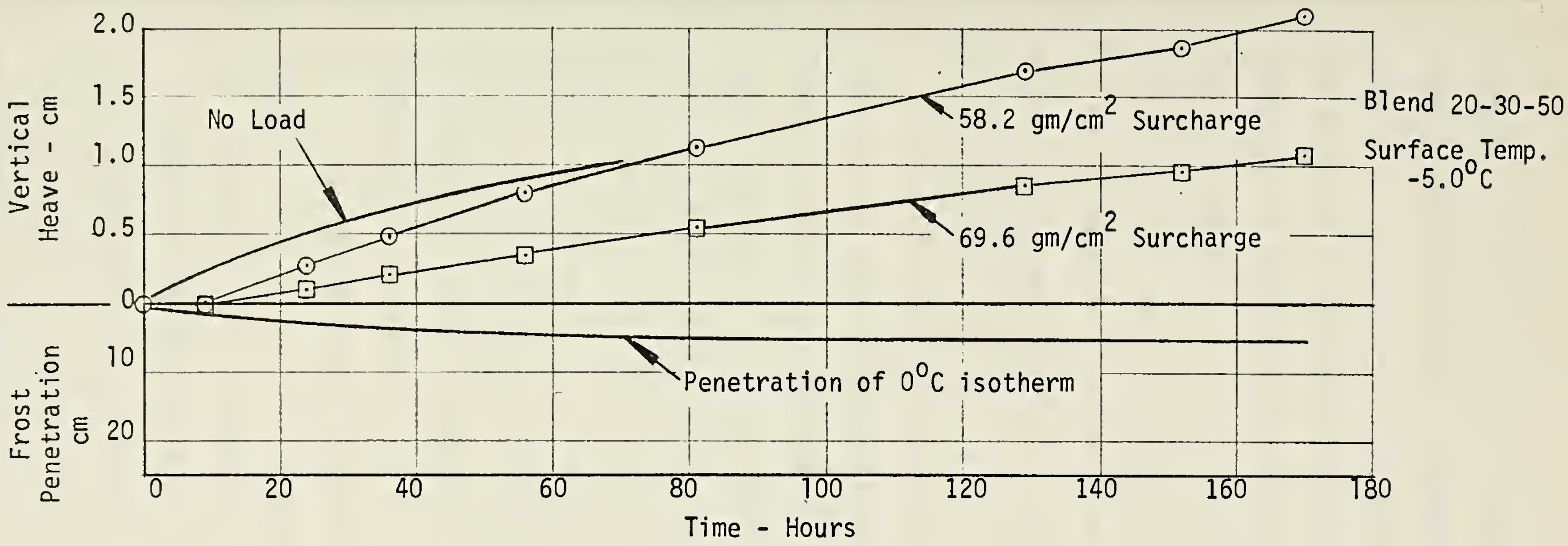
The relationship of σ_2 and σ_3 to σ_1 is known as the coefficient of lateral earth pressure.[24] In the at-rest condition, this value is known as the coefficient of lateral earth pressure at rest, K_o. For an isotropic and homogeneous soil mass, equation (8) can be re-written as:

$$\sigma_{oct} = \frac{1}{3}\sigma_1(1 + 2K_o) \tag{9}$$

Consider the same saturated soil element as above subjected to freezing conditions. Freezing is nucleated within pore space "A." As the ice crystal grows and expands, pressures within the pore space increase. Once the ice crystal fills the initial pore space, one of two reactions takes place: (1) the value of P_i required to develop ice within the pore necks is achieved; or (2) the overburden pressure is overcome and the mass is moved upward. Considering the latter condition, if all three principal stresses acting on the soil element are equal (hydrostatic conditions), the value of P_i can be calculated using strictly the weight of frozen material above. It is well-known that the three stresses are not equal; therefore, the average stress is given by equation 9.

It is theorized by the author that, in calculating the stress (pressure on the ice) at the frost line, the vertical stress as used by Williams[35,37] should be replaced with the octahedral stress. This appears reasonable since the value of P_h in equation (4) is a volumetric mean pressure (see Everett[9]). Therefore, P_i in equation (7) should likewise be a volumetric mean pressure. In order to test this theory, the author re-calculated the surcharge stress needed to stop heave action on the two specimens tested above by setting P_i (equation (7)) equal to σ_{oct} (equation (9)). This resulted in the calculation of the required vertical stress σ_1 needed to be imposed on the surface of the soil (frost line). See Appendix C for sample calculations. Due to time limitations, a one-cycle freeze test of the loaded specimens was conducted at a constant room temperature of $-5.0^{\circ}C$. This room temperature was chosen as it had produced maximum heave under no load conditions of the specimens being tested.

Figure 19 presents the results of the above mentioned test. It is evident that heave action was not stopped; however, the heave was substantially



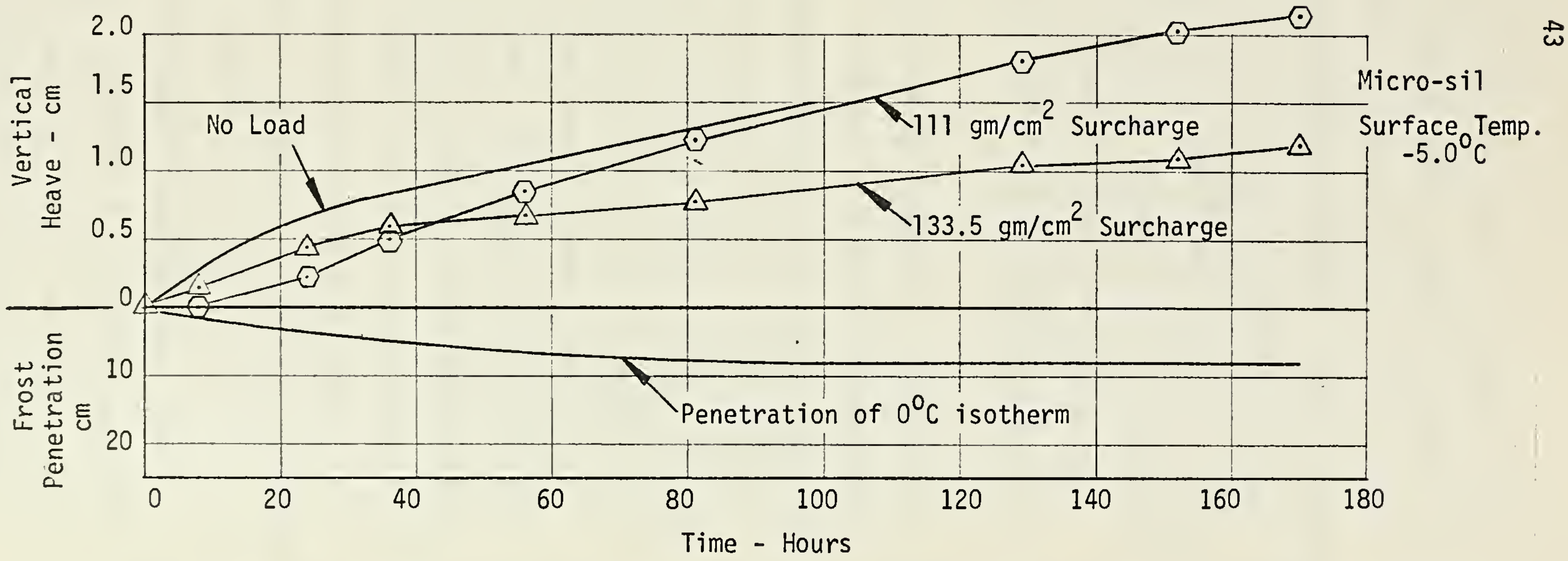


Figure 19. Heave and frost penetration data for loaded specimens of micro-sil and blend 20-30-50.

reduced. In the case of the blend 20-30-50, the use of a K_o value as calculated in the stress meter, reference (25), yielded a reduction of about 50 percent in the heave value compared to unrestricted heave. In the case of the micro-sil specimen, the reduction was about 40 percent. The two specimens loaded with a reduced surcharge value (20% less than calculated), yielded almost no reduction in heave. The results of this freeze test would indicate that the coefficient of lateral earth pressure at rest, K_o, for a given soil has an influence in determining the required amount of surcharge stress needed to stop heave action. This requires further investigation both in the laboratory and in the field.

Figure 20 presents a plot of air-intrusion pressure vs. average heave rates for the five specimens tested. The trend in this data indicates that higher air-intrusion pressures are associated with higher heave rates. This trend is reasonable as the theoretical considerations of the air-intrusion pressure indicates higher pressures are related to smaller pores. In turn, smaller pores in the soil matrix are associated with ice lens growth, i.e. higher heave rates. It is also to be noted that specimen 20-50-30, see Figure 9, coincides with Casagrande's lower limit above which considerable ice segregation may be expected in very uniform soils. From this limited investigation, it appears that an air-intrusion value of 1 psi coincides with this limit. The author therefore speculates that soils which show an air-intrusion value of less than 1 psi can be considered as non-frost-susceptible. This proposed boundary condition is so noted in Figure 20.

Just prior to the completion of this thesis investigation, a report by Aitken[1] was received which reported the results of a six-year investigation into the effects of surcharge stress in reducing heave. The investigation was conducted in Fairbanks, Alaska with natural (undisturbed) soil under

natural seasonal freezing conditions. Normal heave was in the order of 0.5 feet. The application of a surcharge stress of 2.3 psi reduced this by over 30%; a stress of 8 psi resulted in a reduction of about 75%. Unfortunately, calculations for the determination of the surcharge stress are not provided. It would be valuable to compare the results of air-intrusion tests of this material (Fairbanks Silt) and the theorized surcharge stress required to stop heave as calculated using equation (7) with the field investigation results.

One additional test was conducted to assess the reaction of a natural soil to freezing as compared to the Ottawa Sand used in this investigation. A natural soil, QRC Silt, was available which was similar in gradation to the micro-sil. The gradations are shown in Figure 9. Samples of the two soils were placed in a divided freezing cell and subjected to freezing conditions. The observed amount of heave was almost identical for each specimen. Observation of the specimen after freezing revealed that the ice segregation was almost identical in the two different materials. This limited experiment further confirms the importance of particle gradation in frost action. Plate 4 is a photograph of the condition of the two frozen soils. Ice lenses can be seen as well as the limit to which the freezing front penetrated the soils.

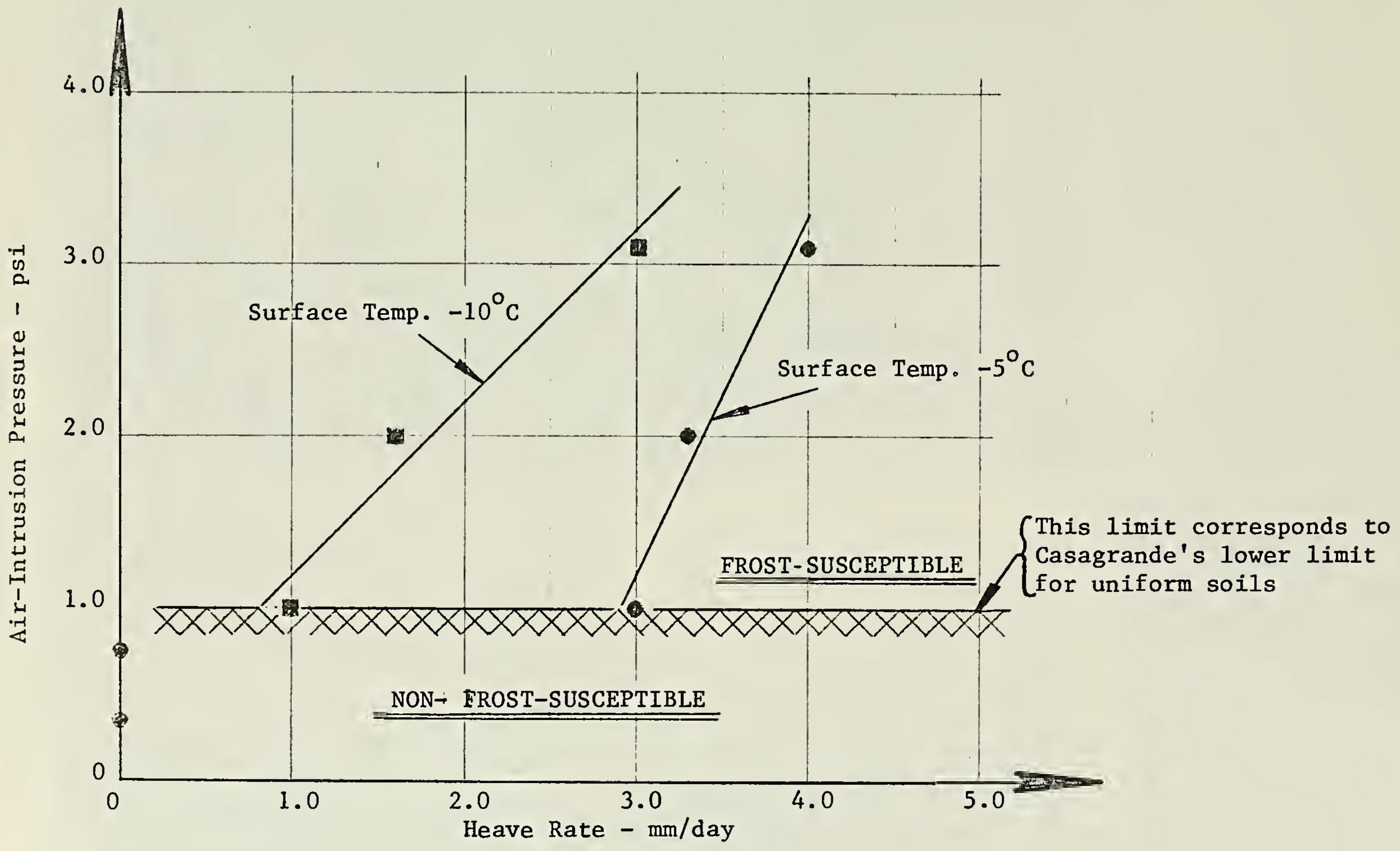


Figure 20. Air-Intrusion Pressure vs Heave Rate

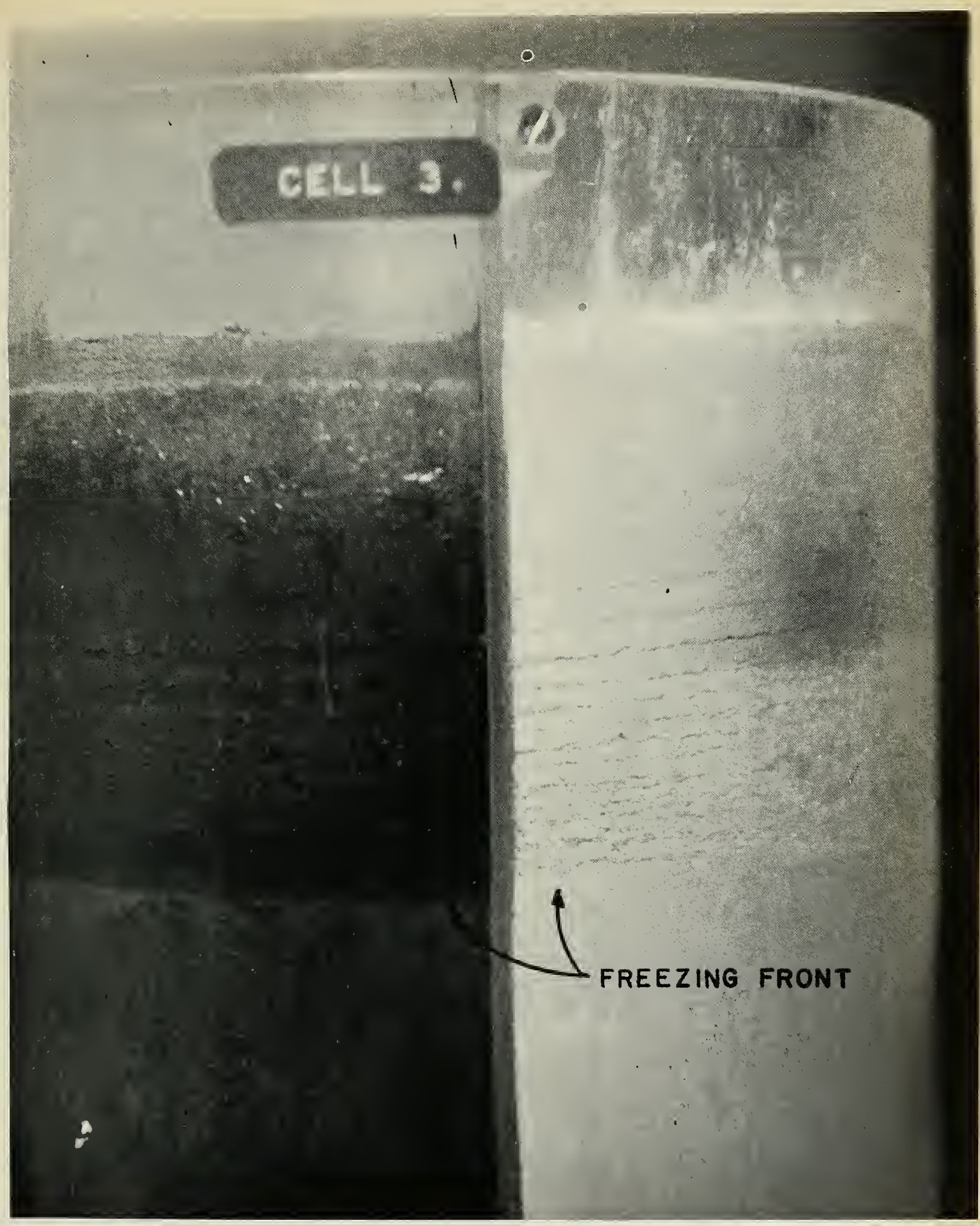


PLATE 4 - Partially Frozen Cylinder, Half Micro-sil, Half QRC Silt - Ice Segregation Similar in Both Soils

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results of a laboratory testing program, consisting of frost heave freezing tests of unloaded and loaded specimens and air-intrusion value determination are presented. The tests were carried out on different gradation of Ottawa Sand. From the results, it can be concluded that:

1. For the five soil gradations investigated, the frost susceptibility criteria as outlined by Casagrande give a meaningful indication of frost action.
2. The time rate of pressure application while performing the air-intrusion test does not substantially effect the resulting air-intrusion value; however, the time effects increase when the size of the soil particles is small. Time intervals between pressure increases of 1 and 2 minutes were found acceptable.
3. Air-intrusion pressure is moisture-dependent, decreasing with increase in moisture content. It was noted that particle segregation occurred when attempting to saturate the specimen as in the case of boiling at a slurry consistency. Higher values of air-intrusion pressure were obtained at moisture contents near the optimum values.
4. Measurement of the air-intrusion value of a soil is performed relatively easily and quickly.
5. Calculated values of required surcharge pressure, as outlined by Williams, did not stop heave altogether; however, heave was substantially reduced as the loads increased.
6. It is theorized by the author that K_o (coefficient of lateral earth pressure at rest) enters into the calculation of the required surcharge pressure to stop heave action. The method of determining

this K_0 value is indicated in reference (26).

7. The heave potential exhibited by the first freeze-thaw cycle is unrepresentative of subsequent cycles. Under test conditions used in this investigation, the heave potential decreased after the initial freeze-thaw cycle. Additional cyclic freeze and thaw did not appear to substantially influence the heave potential. This was true for both loaded and unloaded soil samples.
8. The Tempe Pressure Cell can be used most effectively to perform the air-intrusion test.
9. Soils possessing an air-intrusion pressure of less than 1 psi can be considered as non-frost-susceptible whereas those soils possessing an air-intrusion pressure of 1 psi and above can be considered frost-susceptible. The relative susceptibility of the soil increases as the air-intrusion pressure increases.

Recommendations

The following recommendations are made to assist anyone who wishes to use the testing apparatus described in this thesis or who wishes to continue and expand the investigation:

1. As noted in Chapter III under the description of the insulating cabinet and water reservoir, a means of circulating the water within the reservoir is needed along with a more accurate thermostat.
2. The use of a 1-bar, high flow rate ceramic plate is recommended for use in the Tempe Pressure Cell.
3. In view of the report by Aitken[1] relative to field studies of the effects of surcharge stresses at heave reduction, the obtainment of samples of this natural silt and conduction of air-intrusion tests

using these samples would prove most informative and will provide useful correlations between the laboratory values and field performance.

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APPENDIX A

DETERMINATION OF AIR-INTRUSION VALUE

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DETERMINATION OF AIR-INTRUSION VALUE

The purpose of this appendix is to illustrate the procedure used in determining the air-intrusion value (P_a - P_w) from the observed test data. Included in the appendix is a sample of the author's data sheet, Figure A-1, and a Drainage vs. Time and Pressure vs. Time Plot, Figure A-2.

In order to determine the air-intrusion value, the cumulative drainage is plotted relative to the elapsed time. The point on this curve where acceleration of drainage occurs is the point of air-intrusion into the specimen. The pressure which is being applied to the specimen at the corresponding time is the air-intrusion pressure. This is best illustrated by referring to Figure A-2.

SOIL MECHANICS LABORATORY
UNIVERSITY OF WASHINGTON

AIR-INTRUSION TEST

Soil Sample: OTTAWA SAND Micro-sil
Ceramic Stone # 1
Thickness of Specimen 1.5 cm
Temperature of Specimen 25°C
Buret # A

Test No. 1-9
Date: 6 Aug '74
Tested By: J. Perry

Air-Intrusion Determination:

Elapsed Time min.	Applied Pressure psi	Buret Reading ml	Cumulative Drainage cm^3
0	0.20	2.84	0
1	0.40	2.80	0.04
2	0.60	2.74	0.10
3	0.80	2.65	0.19
4	1.00	2.54	0.30
5	1.20	2.42	0.42
6	1.40	2.29	0.55
7	1.60	2.18	0.66
8	1.80	2.08	0.76
9	2.00	2.01	0.83
10	2.20	1.96	0.88
11	2.40	1.91	0.93
12	2.60	1.88	0.96
13	2.80	1.85	0.99
14	3.00	1.82	1.02
15	3.20	1.80	1.04
16	3.40	1.73	1.11
17	3.60	1.53	1.31
18	3.80	1.29	1.55
19	4.00	1.08	1.76
20	----	0.96	1.88

AIR-INTRUSION PRESSURE
3.20 psi

Moisture Content Determination:

Tare #	P-10
Wt. Wet Sample + Tare	21.66 gm
Wt. Dry Sample + Tare	18.05 gm
Wt. Water in Sample	3.61 gm
Wt. Tare	1.44 gm
Wt. Dry Sample	16.61 gm
Moisture Content (%)	21.7

Remarks: None

Figure A-1. Sample Data Sheet

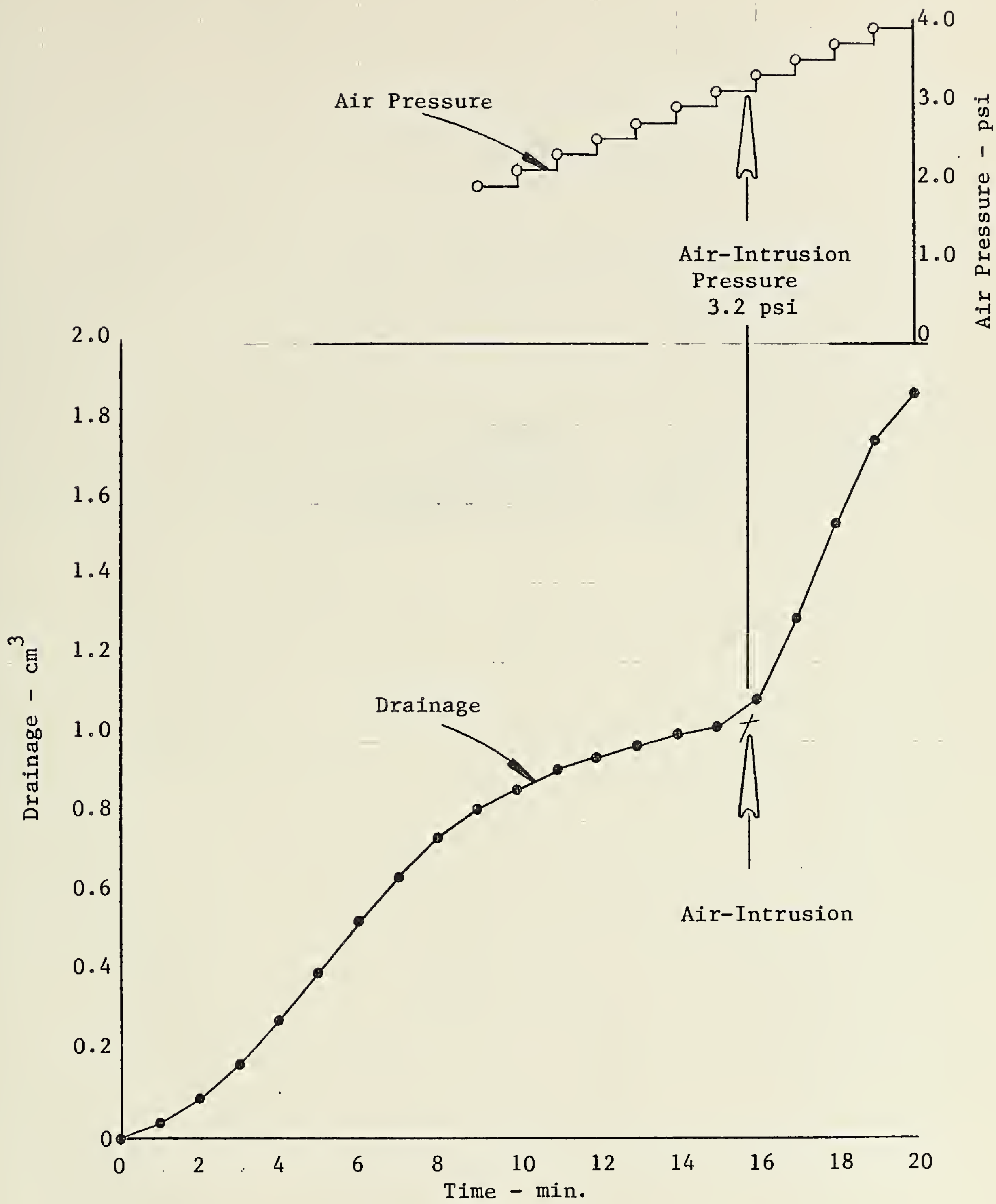


Figure A-2. Drainage vs Time and Pressure vs Time

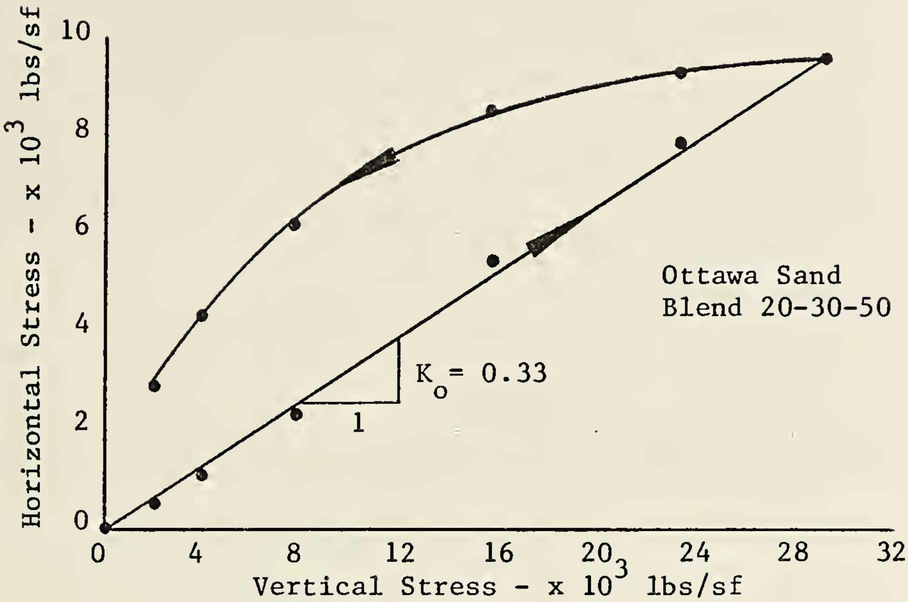
APPENDIX B

DETERMINATION OF K_o VALUE

APPENDIX B

DETERMINATION OF K_o VALUE

The coefficient of lateral earth pressure at rest (K_o) was obtained experimentally using the stress meter testing apparatus developed at the University of Washington.[25,26] Plots of horizontal stress vs. vertical stress were made and the coefficient (K_o) determined directly from the plots. In this test, two trials were made using a dry specimen. Figure B-1 is a typical plot of test results.



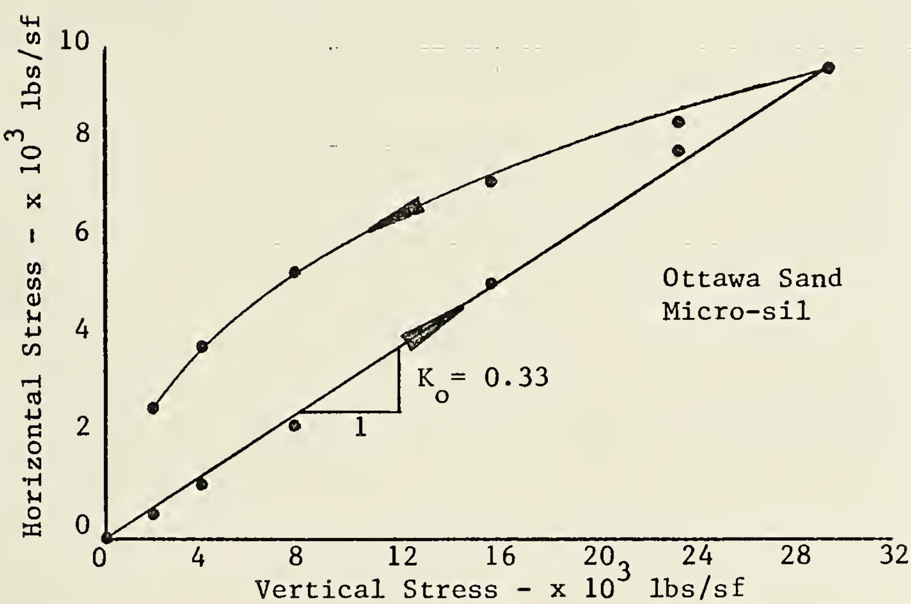


Figure B-1. Horezontal Stress vs Vertical Stress for Blend 20-30-50 and Micro-sil

APPENDIX C

SAMPLE CALCULATIONS

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SAMPLE CALCULATIONS

Equation 7 presents the theoretical relationship between the air-intrusion pressure ($P_a - P_w$) and the ice pressure (P_i) and pore water pressure (P_w). Assuming the ratio $T_{iw}/T_{aw} = 0.42$,[36] the following calculations were made to determine the surcharge stress needed to stop heave action. The load applied to the top of the specimen in the freezing test is the required surcharge stress multiplied by the area of loading plate.

Specimen: Blend 20-30-50
Air-intrusion value - 2.0 psi (140.6 gm/cm^2)
(from air-intrusion test)
Depth to water table - 8" (20.32 cm)

from equation 7,

$$\frac{P_i - P_w}{P_a - P_w} = \frac{T_{iw}}{T_{aw}}$$

therefore:

$$P_i - P_w = \frac{T_{iw}}{T_{aw}} (P_a - P_w)$$

$$P_i = (0.42)\ (140.6) + (-20.32)$$

$$P_i = 38.73\ \text{gm/cm}^2$$

Considering that P_i = surcharge stress, the required surcharge stress = 38.73 gm/cm^2.

SAMPLE CALCULATIONS (continued)

Taking into account the octahedral stress of the soil mass, the following additional calculation is made:

$$P_i = \sigma_{oct} = \frac{1}{3}\sigma_1 (1 + 2K_o)$$

$$\sigma_1 = \frac{3\ P_i}{1+2K_o}$$

$$\sigma_1 = \frac{(3)\ (38.73)}{1 + 2(\frac{1}{3})}$$

$$\sigma_1 = 69.6\ \text{gm/cm}^2$$

Thus, σ_1 x area of loading plate equals the total surcharge placed on the specimen during the freezing test.

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